
Crew Factors in Flight Operations IX: Effects of Planned Cockpit Rest on Crew Performance and Alertness in Long-Haul Operations

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PREFACE

This study spanned several years and involved the important contributions of many, including the following individuals, agencies, and institutions.

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LIST OF ABBREVIATIONS

ASRS	Aviation Safety Reporting System
CNS	central nervous system
EEG	electroencephalogram
EMG	electromyogram
EOG	electrooculogram
FAA	Federal Aviation Administration
FO	First Officer
HNL	Honolulu, HI
LAX	Los Angeles, CA
LED	light-emitting diode
L/O	layover
MSLT	Multiple Sleep Latency Test
NREM	non-REM
NRG	no-rest group
NRT	Tokyo - Narita, Japan
NTSB	National Transportation Safety Board
OSA	Osaka, Japan
PSG	polysomnography
PVT	psychomotor vigilance task
REM	rapid eye movement
RG	rest group
RT	reaction time
SEA	Seattle
SEL	Seoul
SEM	slow-rolling eye movement
SO	Second Officer
TOC	top of climb
TOD	top of descent
TSWS	total slow-wave sleep
TS1	total stage 1 (sleep)
TS2	total stage 2 (sleep)
WAM	wrist activity monitor

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SUMMARY

The primary goal of this study was to determine the effectiveness of a planned cockpit rest period to improve alertness and performance in long-haul flight operations. Twenty-one pilots participated and were randomly assigned to either a Rest Group or a No-Rest Group condition. The Rest Group was allowed a planned 40 min. rest period during the low workload, cruise portion of flight. The No-Rest Group had a 40 min. planned control period identified but maintained their usual flight activities during this time.

Several measures were used to examine the physiological, behavioral, performance, and subjective effects of the nap, including continuous ambulatory recordings of brain wave and eye movement activity, a reaction time/vigilance task, and a wrist activity monitor. Subjective measures collected in the study included in-flight fatigue and alertness ratings, a daily log for noting sleep periods, meals, exercise, flight and duty periods, and the NASA Background Questionnaire.

The results indicated that the Rest Group pilots were able to sleep during the cockpit rest period, generally falling asleep quickly and sleeping efficiently. This nap was associated with improved physiological alertness and performance compared to the No-Rest Group. The benefits of the nap were observed through the critical descent and landing phases of flight. The convergence of the behavioral performance data and the physiological data to demonstrate the effectiveness of the cockpit nap lend support to the robustness of the findings. The nap did not affect layover sleep or the cumulative sleep debt displayed by the majority of crewmembers. The nap procedures were implemented with minimal disruption to usual flight operations and there were no reported or identified concerns regarding safety.

The planned nap appeared to provide an effective, acute relief for the sleepiness experienced in nonaugmented 3-person long-haul flight operations. The strength of the current results supports the implementation of planned cockpit sleep opportunities in nonaugmented long-haul flight operations involving 3-person crews. If implemented, we recommend a follow-up study be conducted to examine how planned cockpit sleep opportunities have been incorporated into airline procedures. The results of this follow-up study may lend support for further refinement of procedures and future implementation through Federal regulation.

1.0 OPERATIONAL SUMMARY

This report is the ninth in a series on physiological and psychological effects of flight operations on flight crews, and on the operational significance of these effects.

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Long-haul flight operations often involve rapid multiple time-zone changes, sleep disturbances, circadian disruptions, and long, irregular work schedules. These factors can result in fatigue, cumulative sleep loss, decreased alertness, and decreased performance in long-haul flight crews. Thus, operational effectiveness and safety may be compromised because of pilot fatigue. One natural compensatory response to the sleepiness and fatigue experienced in long-haul operations is unplanned, spontaneous napping and non-sanctioned rest periods. That these activities occur is supported by anecdotal, observational, and subjective report data from a variety of sources. In response to this information and to concerns for maintaining flight safety, it was suggested that a planned cockpit rest period could provide a "safety valve" for the fatigue and sleepiness experienced in long-haul flying. The cockpit rest period would allow a planned opportunity to sleep, with the primary goal being to improve subsequent levels of performance and alertness, especially during critical phases of operation such as descent and landing.

This study was co-sponsored and sanctioned by the FAA and involved the voluntary participation of two commercial airlines. The primary goal was to determine the effectiveness of a planned cockpit rest period to improve performance and alertness in nonaugmented, three-person long-haul flight operations. Twenty-one volunteer pilots participated and were randomly assigned to either a rest group (N = 12) or a no-rest group (N = 9) condition. The rest group (RG) was allowed a planned 40 min. rest period during the low-workload, cruise portion of flight over water. Pilots rested one at a time, on a prearranged rotation, with two crewmembers maintaining the flight at all times. The no-rest group (NRG) had a 40 min. planned control period identified during cruise but maintained their usual flight activities during this time. The four consecutive middle legs of a regularly scheduled transpacific trip, part of a 12-day trip pattern, were studied. Two legs were westbound day flights and two legs were eastbound night flights, with generally comparable flight and duty times.

Specific procedural and safety guidelines were successfully implemented in this initial study. However, not all of these would be necessary for a general implementation of planned cockpit rest periods in long-haul flight operations: (1) it was crucial that the rest period was planned, with first choice of rest period going to the landing pilot; (2) the rest periods were scheduled during a low-workload phase of flight and ended 1 hr. before descent; (3) only one crew member was scheduled to rest at a time with a clear planned rotation established; (4) the rest opportunity was divided into an initial preparation period (3 min.), followed by the 40 min. rest period, followed by a recovery period (20 min.) (these times might be altered to reduce the overall length of the period); (5) the rest was terminated at a preset time by a researcher, and the resting pilot was fully briefed before reentering the operational loop; and (6) it was established that the captain would be notified immediately at the first indication of any potential anomaly. The safe and normal operation of the aircraft was given the highest priority and, therefore, no cockpit rest procedure or activity was allowed to interfere with this.

Several measures were used to examine the physiological, behavioral, performance, and subjective effects of the planned cockpit nap. Continuous ambulatory recordings of brain wave and eye movement activity were conducted to determine physiologically how much sleep was obtained during the rest period, as well as the time taken to fall asleep and the stages of sleep. (These recordings allowed differentiation of non-rapid-eye-movement [NREM] sleep and its stages and rapid-eye-movement [REM] sleep). A reaction-time/sustained-attention task (psychomotor vigilance task) was used to assess performance capability. A wrist activity monitor was worn continuously before, during, and after the trip schedule. This activity monitor provided information regarding the pilots' 24 hr. rest/activity pattern and was used to examine layover sleep episodes. Subjective measures collected in the study included in-flight fatigue and alertness ratings, a daily log for noting sleep periods, meals, exercise, flight and duty periods, etc., and the NASA Background Questionnaire.

The physiological data showed that on 93% of the rest period opportunities the RG pilots were able to sleep. Generally, they fell asleep quickly (average = 5.6 min.) and slept for an average of 26 min. There were six factors related to sleep quantity and quality that were analyzed: total sleep time, sleep efficiency, sleep latency, percent NREM stage 1 sleep, percent NREM stage 2 sleep, and percent NREM slow-wave sleep. Each of these factors was examined for effects related to trip leg, halves of the trip, day versus night, and flight position (captain, first officer, second officer).

There were two significant effects that emerged from these analyses. The day flights had significantly more light sleep than night flights, and the night flights had significantly more deep sleep than day flights. An interesting finding emerged from analysis of the physiological data collected during the NRG 40 min. control period. Although instructed to continue usual flight activities, four NRG pilots fell asleep (a total of five episodes) for periods lasting from several minutes to over 10 min.

There were generally consistent findings for the variety of analytical approaches used to examine the performance data. The median sustained attention/reaction time (a performance measure) for the NRG showed a greater range of average responses across flight legs and during in-flight trials than seen in the RG. After leg 1, the pilots in the NRG showed a steady increase in median reaction time across flight legs, with significant differences by the middle and end of flights. The RG pilots maintained a generally consistent level of performance both across and within flight legs, and did not show significant increases in reaction time. There were a total of 283 lapses (i.e., a response delay > 0.5 sec.) for all 21 pilots (both groups combined). For in-flight trials, the NRG (with fewer subjects) had a total of 124 lapses, whereas the RG had a total of 81. There was an increase in lapses during in-flight trials 2 and 3 (after the test period) for the NRG, though this increase did not occur during in-flight trials following the nap in the RG. Both groups had more lapses before top of descent (TOD) on night-flight leg 4 than on night leg 2. However, the number of lapses in the NRG pilots increased twice as much as in the RG pilots. Vigilance decrement functions also revealed that on night flights the NRG pilots had a level of performance that was significantly decreased relative to the RG pilots. Generally, the performance task demonstrated decrements across flight legs and within flights for the NRG, whereas the RG maintained consistent levels of performance. These findings suggest that the planned nap prevented deterioration of vigilance performance.

Changes in brain wave and eye movement activity can reflect the subtle ways that physiological alertness/sleepiness changes. An intensive critical phase analysis was conducted to examine the effects of the cockpit nap on subsequent physiological alertness. The period from 1 hr. before TOD through descent and landing was analyzed for the occurrence of brain and eye movement microevents indicative of reduced physiological alertness. During approximately the last 90 min. of flight, each event greater than 5-sec. duration was scored for both the NRG and RG. There was at least one such microevent identified in 78% of the NRG and 50% of the RG. Overall, there were a total of 120 microevents that occurred in the NRG (with fewer subjects) and a total of 34 microevents in the RG. The NRG averaged significantly more total microevents (6.37) than the average in the RG (2.90). This supports the conclusion that the sleep obtained during the rest period was followed by increased physiological alertness in the RG relative to the NRG.

The 24 hr. rest/activity patterns, in combination with the subjective logs, demonstrated that 86% of the 21 subjects accumulated a sleep debt that ranged from 4 to 22 hr. and averaged approximately 9 hr. by the ninth day of the duty cycle. When the entire 36 hr. duty period (layover and subsequent duty cycle) is considered, the percent of layover sleep time is 28%. This is less than the average 33% sleep time spent off-duty at home, hence the cumulative sleep debt. One subject gained sleep, and two others had no change. Further analysis demonstrated that the cockpit nap did not significantly alter the cumulative sleep debt observed in the RG. Also, 77% of the layovers involved more than one sleep episode. Generally, there were two sleep episodes, and if the first one was long, then the second one was short or did not occur. Conversely, if the first sleep episode was short, then there was almost always a second one that was long. This result demonstrated that there were multiple factors operating to control sleep timing and quantity (e.g., local time, home circadian time, prior sleep loss). This study was not designed to examine the issue of layover sleep periods, though recently the timing of layover sleep periods, including naps, in long-haul flight operations has been addressed.

Overall, the analysis of the subjective alertness ratings demonstrated that pilots reported lower alertness on night flights than on day flights and after the rest/control period than before it (except on leg 1). The results indicated that the nap did not affect the subjective ratings of alertness, though the objective measures clearly indicated better performance and greater alertness in the RG. The level of physiological sleepiness experienced in long-haul flight operations was demonstrated in both subject groups. The speed of falling asleep has been used as a measure of

physiological sleepiness (i.e., the more sleepy an individual, the faster he or she will fall asleep). The speed of falling asleep in the RG (5.6 min.) is comparable to that seen in moderately sleep deprived individuals. A diagnostic guide for excessive sleepiness in sleep disorder patients is a sleep latency of 5 min. or less. Also, there were five episodes of sleep that occurred during the control period in four NRG pilots who had been instructed to continue usual flight operations. This result reinforces previous findings that pilots are poor evaluators of their level of physiological sleepiness.

Overall, the study results provide support for differentiating fatigue countermeasures into two basic approaches. Conceptually and operationally, methods to minimize or mitigate the effects of sleep loss, circadian disruption, and fatigue in flight operations, can be divided into (1) preventive strategies and (2) operational countermeasures. Preventive strategies involve those approaches that result in more long-term adjustments and effects on underlying physiological sleep and circadian processes (e.g., possibilities for further research include shifting the circadian phase before multiple time-zone changes, using bright lights or exercise to rapidly readjust the circadian clock, and maximizing the quantity and quality of sleep). These preventive strategies affect underlying physiological sleep need, sleepiness, and circadian phase in a long-term and chronic fashion. Operational countermeasures are focused strategies for reducing sleepiness and improving performance and alertness during actual operations (e.g., proved strategies include judicious use of caffeine, increased physical activity, and increased interaction). These short-acting countermeasures are not intended to reduce underlying physiological sleepiness or a sleep debt, but rather to increase performance and alertness during operational tasks. One acute, short-acting operational countermeasure that can temporarily reduce physiological sleepiness is napping. The planned cockpit nap in this study is considered to be an operational countermeasure that provided an acute, short-acting improvement in performance and alertness.

It must be acknowledged that every scientific study has specific limitations that restrict the generalizability of the results. This study involved only one trip pattern on a commercial airline carrier. The study was conducted on transpacific flights to utilize the opportunity of scheduling the planned rest periods during the low-workload portion of cruise over water. The intense physiological and performance data collection occurred during a specific and restricted middle segment (four consecutive flight legs) of the trip schedule. Therefore, the initial home-to-flight-schedule transition is quantified only with logbook and activity data. Also, the highest levels of accumulated fatigue, which probably occurred during the final trip legs, were not studied except for logbook and activity data. This study involved B-747 aircraft flown by three-person crews; the specific application of this countermeasure to the two-person cockpit was not addressed.

There were two NASA researchers on the flight deck during the in-flight data collection periods. Although they were instructed to minimize their interactions and presence, there is no question that having two extra individuals on the flight deck may have potentially altered the regular flow of cockpit conversation and interaction. It is important to remain cognizant of these limitations when attempts are made to generalize the study results to questions that extend beyond the scope of the specific scientific issues addressed here.

In conclusion, the RG pilots were able to sleep during the planned cockpit rest period, generally falling asleep quickly and sleeping efficiently. This nap was associated with improved performance and physiological alertness in the RG compared to the NRG. The benefits of the nap were observed through the critical descent and landing phases of flight. The convergence of the behavioral performance data and the physiological data to demonstrate the effectiveness of the cockpit nap lend support to the robustness of the findings. The nap did not affect layover sleep or the overall cumulative sleep debt displayed by the most of the crewmembers. The nap procedures were implemented with minimal disruption to usual flight operations, and there were no reported or identified concerns regarding safety.

The planned nap appeared to provide an effective, acute relief for the fatigue and sleepiness experienced in nonaugmented three-person long-haul flight operations. The strength of the current results supports the implementation of planned cockpit sleep opportunities in nonaugmented long-haul flight operations involving three-person crews. If planned cockpit sleep opportunities were sanctioned, each airline could determine the appropriate incorporation of procedures into its specific mode of operation. If implemented, we recommend that a joint NASA/FAA follow-up

study be conducted within 6-12 months to examine how planned cockpit sleep opportunities have been incorporated into airline procedures. That study would examine how the procedures were implemented and their effectiveness. This might take the form of a survey or include some field data collection. The results of that follow-up study might then lend support for further refinement of procedures and future implementation in other flight environments.

2.0 INTRODUCTION

2.1 Background

The rapid multiple time-zone changes, sleep disturbances, circadian disruptions, and long, irregular work schedules associated with long-haul flight operations can result in pilot fatigue. Safety and operational effectiveness during long-haul flights may be compromised because of reduced pilot performance and alertness. Pilot fatigue in long-haul flight operations is a major safety concern.

Several sources lend support to this concern. Long-haul wide-body flight operations have almost a three-times higher loss ratio than combined short- and medium-range flights (ref. 1). Also, cockpit crew error, where pilot fatigue may be a contributory factor, has been related to 75% of aircraft losses since 1959 (ref. 1). NASA's Aviation Safety Reporting System (ASRS) receives reports every month from long-haul crews describing the role of fatigue, sleep loss, and sleepiness in significant operational errors. Reported errors have included altitude deviations, improper fuel calculations, track deviations, landings without clearance, and landings on incorrect runways. These reports are not surprising, for many pilots describe anecdotally the overwhelming fatigue and sleepiness associated with all-night flying over the ocean. The flight deck environment, with constant background noise, dim lighting, and various levels of automation, can contribute to the difficulty of remaining vigilant and awake under these circumstances. As trips progress and as the number of flight legs increases, so too can the cumulative effects of sleep loss and fatigue.

Extensive research has shown that there are at least three interrelated biological sources of the fatigue, sleep loss, and sleepiness experienced in long-haul flight operations (e.g., refs. 2-4): (1) circadian disruption, (2) cumulative sleep loss, and (3) sleepiness rhythm. Each of these factors will be reviewed briefly to provide greater understanding and background for the causes of fatigue and sleepiness in long-haul flying.

Human circadian (i.e., about 24 hr.) rhythms are internally controlled by a biological clock in the brain. There are many examples of biological functions that fluctuate over a 24 hr. period, such as sleep and wakefulness, body temperature, and activity. Transmeridian flights rapidly transport this internal human circadian clock to new external time zones. The internal biological clock, however, is unable to adapt quickly and instead adjusts to the new external time zone at a slow rate. The result is a desynchrony between biological rhythms and external synchronizers (e.g., light, meals) and a disorganization of internal physiological and psychological rhythms as the circadian clock slowly adjusts to the new environmental time. Most pilots are familiar with these factors as primary causes of their experience of fatigue and other symptoms of jet lag. It has been shown that the severity of circadian adjustment effects is related to the number of time zones crossed. The more time zones crossed, the greater the adjustment required by the circadian clock. It is also known that there are wide individual differences in ability to adjust to new time zones. Some individuals can experience severe effects following a time-zone change of only 1 or 2 hr.

One basic biological property of the human circadian clock accounts for the generally familiar experience of easier and faster adjustment when flying west than when flying east. If allowed to run at its natural rhythm, the average internal biological clock would actually have a cycle slightly longer than our 24 hr. day, about 25 hr. This means that there is a natural, inherent tendency to lengthen our day. Therefore, when traveling a westward, the circadian day is lengthened (or delayed) and promotes adjustment to the new time zone. Conversely, when flying eastward the

circadian day is shortened (or advanced), contrary to the natural tendencies of the internal clock. Therefore, generally, adjustment will be slower and more difficult.

A second primary consequence of circadian disruptions by rapid time-zone changes is that the sleep/wakefulness rhythm is out of phase, or desynchronized, with the new environmental time. For example, pilots may attempt to sleep at the new environmental night time, when their internal circadian clock says it is high noon and they should be wide awake. The result is usually sleep loss caused by a short-duration sleep, often precipitated by a premature spontaneous awakening. Over time, this shortened sleep duration results in a cumulative sleep loss and sleep debt. For example, if an individual gets 1 hr. less sleep per night than is usually needed, by the end of 1 week he or she will have accumulated the equivalent hourly loss of a full night's sleep. The severity of the sleep disturbance will affect the total cumulative sleep debt. However, the loss of even 1 hr. of sleep will contribute to increased waking sleepiness, with the potential effect being even greater when combined with prior cumulative sleep loss (ref. 5). The potential results of sleep loss are performance lapses, slowed mental processing and decision-making, reduced memory function, and more negative mood (ref. 6).

Scientific research has shown that separate from nocturnal sleep, the biological clock also regulates the daily level of sleepiness and alertness, that is, sleepiness rhythm. In a 24 hr. period, there are two distinct periods of maximal sleepiness for a normal, healthy, nonsleep-deprived person: during the early morning hours (about 4-5 A.M.) and during the mid-to-late afternoon hours (about 3-5 P.M.) (ref. 7). Typically, individuals would attempt to be asleep during the 4-5 A.M. period of sleepiness, when there are minimal environmental distractions and a decreased body temperature. Also, most people have experienced the increased sleepiness that occurs during the mid-to-late afternoon, which is when most naps are taken (ref. 8). During the afternoon most individuals are active, and in an environment with stimulation, and the body temperature is high, allowing them to continue their activities without being overcome by sleepiness. These internally controlled periods of maximal sleep tendency greatly enhance the likelihood that sleepiness, and perhaps sleep, will intrude into wakefulness. Although a variety of strategies are used to combat this period of biological sleepiness, it is clearly a window of increased vulnerability to reduced performance and alertness. It is also known that sleep loss exacerbates this situation by increasing the level of sleepiness at all times of the day. This information is important in identifying periods of maximal physiological sleepiness that occur every 12 hr. If a night flight over the ocean coincides with a window of maximal sleepiness, then there is an increased vulnerability to involuntary sleepiness.

These three factors interact and provide the physiological basis for the fatigue, sleep loss, and decreases in alertness, performance, mood, and mental function associated with long-haul flight operations. One compensatory response to this fatigue, sleep loss, and sleepiness is the occurrence of involuntary sleeping in the cockpit, with increased frequency of occurrence during night flying (refs. 9, 10). Evidence, beyond the purely anecdotal, suggests that this is occurring in long-haul flight operations. One operational study reported observational data from three-person commercial airline crews flying international routes (ref. 10). The flight deck observers on these flights noted any episode when crewmembers apparently napped while in their cockpit seat. In conjunction with the daily log and observer notes, the results indicated that crewmembers napped, depending on the specific trip schedule, on from 5% - 20% of the flights available for cockpit napping. Generally, these naps were reportedly unplanned, though at times a crewmember would inform the others of a need for a brief rest period.

It was suggested that these percentages are most likely underestimates of the actual incidence of napping, planned or otherwise, in long-haul flight operations. Recently, Gander et al. reported data based on crew's subjective logs that indicated the timing and duration of their naps (ref. 3). The log data indicated that on average, 11% of crewmembers reported taking naps on the flight deck when an opportunity was available during a flight. These naps ranged from 10-130 min. in length and averaged 46 min. It is unclear from these data which naps were planned and which involved uncontrolled, involuntary napping.

Current civil aviation regulations do not sanction sleep in the cockpit, though it is unclear how often this strategy is actively used to overcome sleepiness and fatigue during long-haul transmeridian flights (ref. 11). The U.S. Air Force and some foreign carriers currently use cockpit

rest periods to combat fatigue. The potential for devastating consequences as a result of increased sleepiness and fatigue and the associated decrease in vigilance and performance are compelling reasons to address these complex issues through operationally relevant empirical research.

2.2 Cockpit Rest Periods: Relevant Laboratory Research

Based on scientific and operational considerations, Graeber, et al. have suggested that planned and controlled napping on the flight deck may be one way of overcoming the sleepiness and decreased performance that can be associated with nonaugmented long-haul flying (ref. 12). Empirical research data in both laboratory and field experiments support this notion. A brief, planned nap can minimize the adverse behavioral, physiological, and psychological effects of sleep loss and circadian desynchronization (refs. 13-16). Generally, most healthy young adults can nap on demand, even in a lighted room with sounds, if sitting in a comfortable chair (refs. 17, 18).

Naps can have a beneficial effect on self-reported alertness in nonsleep-deprived individuals and on sustained performance in sleep-deprived individuals (for a review see refs. 8, 19). Research indicates that taking a nap before a significant sleep-debt accumulation is more important to its effectiveness than the circadian position (refs. 13, 14). Thus “prophylactic napping” can prevent some of the effects of sleepiness (ref. 13). The scientific literature, therefore, supports the proposition that planned and controlled napping on the flight deck may be an effective countermeasure to the fatigue and sleepiness experienced in long-haul flight operations.

The length of the planned cockpit rest periods is considered to be a critical factor. Laboratory research has suggested that a brief nap, less than 1 hr. long, would be sufficient to improve subsequent alertness and performance (ref. 8). A longer nap increases the possibility that deep sleep will occur and, therefore, might increase the potential effects of sleep inertia (i.e., the sleepiness that can be experienced when one is awakened from deep sleep). For a more complete discussion of these issues and the relevant laboratory research, see reference 20.

2.3 Purpose

The primary goal of this research was to examine the effects of a planned cockpit rest period on pilot performance and alertness in long-haul nonaugmented flight operations. It was hypothesized that a short, planned opportunity to sleep during a low-workload portion of flight (i.e., cruise) would act as a “safety valve” for fatigue and sleepiness. Performance and alertness following the nap should be improved, especially during critical phases of operation, such as descent and landing.

2.4 Scientific and Operational Issues

This research was designed to examine a variety of basic issues. The following are some of the specific questions that were addressed:

1. Given the opportunity, will pilots be able to sleep in their cockpit seats? What will be the quantity and quality of the sleep obtained in the cockpit environment?
2. Will a nap improve subsequent performance, such as sustained attention or vigilance, or prevent it from worsening? Will performance be maintained or improved during critical phases of operation, such as descent and landing?
3. Will a nap improve subsequent alertness, as indicated by physiological measures of alertness/sleepiness, or prevent it from worsening? Will alertness be maintained or improved during critical phases of operation, such as descent and landing?
4. If a planned nap improves performance and alertness, how long do the positive effects last?
5. Could planned rest opportunities, and sleep, compromise flight safety?

6. What operational guidelines should be considered for implementation of planned cockpit rest in long-haul operations?
7. Would planned cockpit rest be an improvement over the current situation of uncontrolled spontaneous napping in nonaugmented long-haul flying?

3.0 METHODS

3.1 Study Design Overview

This study involved regularly scheduled transpacific flights with nonaugmented B-747 three-person crews. Volunteer pilots were randomly assigned to one of two study groups. The rest group (RG) was allowed a 40 min. opportunity to sleep during the overwater cruise portion of flight. On a rotating basis, individual crewmembers were allowed to nap in their cockpit seat. The no-rest group (NRG) was not offered a nap opportunity, and instead performed their usual operational activities throughout the flight.

Before the study began, briefings regarding the operational and scientific goals of the project were held with the Federal Aviation Administration (FAA), the National Transportation Safety Board (NTSB), airline management, and pilot union officials. The FAA co-sponsored the project and provided crucial support through its sanction for cockpit rest. It was vital that all concerned parties be informed and support the project. The two airlines approached agreed to participate in the study. Each airline's participation was dependent on the availability of specific transpacific trip schedules and volunteer pilots.

3.2 Subjects

All subjects were line pilots who volunteered to participate in the study. The data in this report were based on pilots flying the regularly scheduled transpacific trip outlined in the next subsection. After this specific schedule had been selected, the trip was marked in subsequent bid packages to indicate that pilots bidding this trip would be contacted by NASA researchers for volunteer participation in a fatigue study. Once pilots were assigned to the trip, a NASA principal investigator contacted them regarding the project. Initial contact was by letter and telephone with a description of the ongoing NASA program to study crew fatigue and jet lag and an outline of the proposed study. The specific requirements of participation were described in detail and questions or concerns were addressed thoroughly. It was clearly indicated that involvement would be completely confidential, that the FAA and their airline had sanctioned the cockpit rest, and that their participation was completely voluntary at all times, including once they had begun the protocol. Therefore, volunteers were informed that they could withdraw at any point in the study. No financial or other remuneration was offered or provided for participation. If pilots volunteered, then information packets (written and video materials), questionnaires (e.g., logbooks), and some equipment (e.g., actigraphs) were given to them.

It has been the general policy of this NASA Fatigue Countermeasures Program to provide complete confidentiality and anonymity for all pilots participating in studies. This effect required additional sanctions and guarantees by the FAA and participating airlines for pilots in the rest group to be allowed a cockpit rest period. Participating volunteers were assigned an identification code that was used for all data collected. Only identification numbers were associated with any identifiable component of the project.

3.3 Trip Characteristics

The specific trip pattern studied was chosen to meet certain scientific and operational conditions. These conditions included multiple transpacific crossings, some equal groupings of day and night flights, comparable flight lengths, regularly scheduled, nonaugmented crews, low

workload (cruise) portions of flight over water, and a trip of sufficient length that fatigue would be a factor.

The middle four legs of an eight-leg regularly scheduled trip pattern were studied. The trip schedule is outlined in table 1, where asterisks indicate the departure and destination airports of the four study legs. The overall trip schedule and study legs are shown geographically in figure 1.

Table 1. Study trip schedule

Trip Leg	Study Leg	From	To	Flight Time	Duty Time	L/O Time
1		SEA	NRT	9.9	12.9	26.4
2		NRT	HNL	6.7	8.4	22.2
3	1	HNL*	OSA*	9.5	10.6	29.4
4	2	OSA*	HNL*	6.9	9.1	25.4
5	3	HNL*	NRT*	8.9	9.9	24.3
6	4	NRT*	LAX*	9.7	11.7	25.0
7		LAX	SEL	13.8	14.8	19.3
8		SEL	SEA	9.8	11.6	-----

Note: (L/O = layover; SEA = Seattle; NRT = Narita; HNL = Honolulu; OSA = Osaka; LAX = Los Angeles; SEL = Seoul)

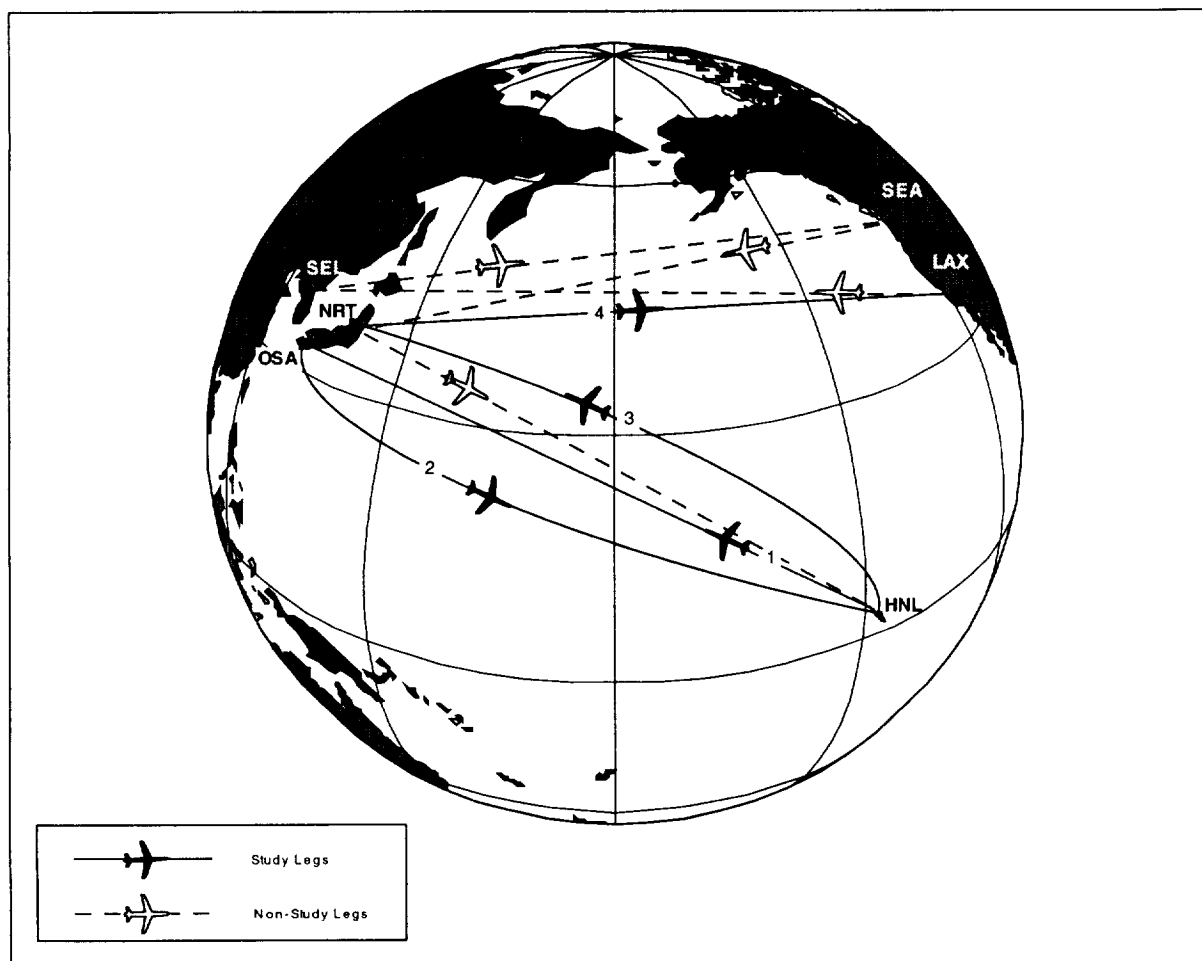


Figure 1. Geographic portrayal of overall trip schedule and study legs.

The entire trip schedule spanned 12 days. The study legs were balanced: two daytime westward legs (study legs 1, 3; trip legs 3, 5) and two nighttime eastward legs (study legs 2, 4; trip legs 4, 6).

Figure 2 shows the cockpit rest study trip profile in greater detail.

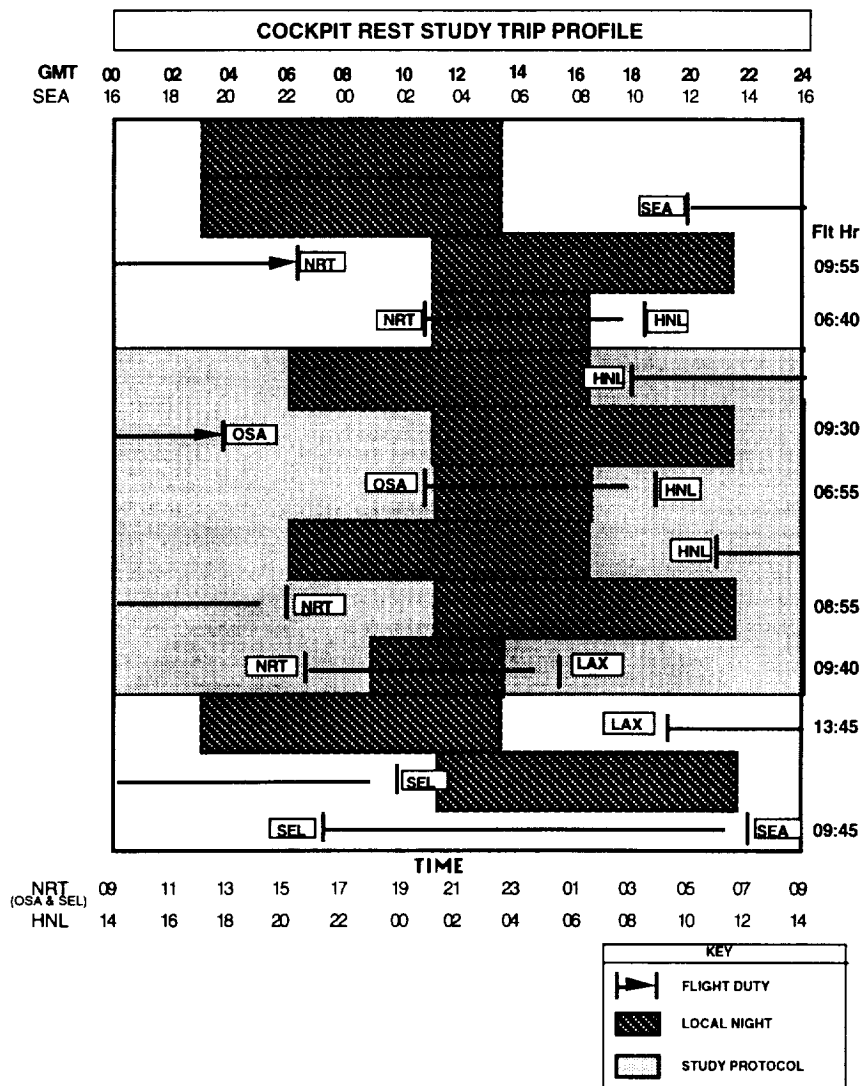


Figure 2. Detailed version of the cockpit rest study trip profile.

3.4 Research Personnel

There were two NASA observers/researchers to implement the procedures and collect data on each trip. Therefore, a two-person team of NASA researchers was assigned to accompany each volunteer crew throughout the four flight legs. The team always had one researcher familiar with aviation and able to take detailed operational notes and one able to conduct the physiological recordings. Once in the field, the NASA team had responsibility for maintaining the integrity of the protocol and determining appropriate responses to unforeseen occurrences. None of the NASA researchers was employed or affiliated with the participating airlines or the FAA. Many others

were also involved in the diverse and complex tasks required to conduct this study. Their roles are highlighted in the preface.

3.5 Measures

Multiple measures (i.e., physiological, behavioral, and subjective) were used to determine the effectiveness of the cockpit rest period in improving subsequent crew performance and alertness. Specific measures were chosen to evaluate the fatigue, sleep loss, sleepiness, and performance associated with long-haul flight operations.

3.5.1 Physiological Measures

A variety of physiological measures was used to discriminate sleep and wakefulness and to measure physiological alertness/sleepiness.

Physiological Recording of Sleep and Wakefulness

The planned cockpit rest period provided an opportunity for a nap, the primary countermeasure evaluated in this study. A crucial question was whether, given the opportunity, pilots would actually sleep during the rest period. Generally, individuals do not accurately describe their sleep. Laboratory studies have demonstrated that normal, healthy individuals, as well as sleep disordered patients, can give subjective reports of their sleep very discrepant from physiological measures of sleep and wakefulness (refs. 21-23). The general trend is that people subjectively report more wakefulness than demonstrated by objective physiological measures of sleep and wakefulness; that is, people get more sleep than they realize. Usually, individuals report taking a longer time to fall asleep and less total sleep time than indicated by physiological data. This known discrepancy between the subjective experience of sleep and physiological sleep was a very important consideration in this study. It was crucial to determine the quantity and quality of physiological sleep that occurred during the rest period, as well as the subjective description of the nap. Therefore, ambulatory physiological recordings were used to determine if crewmembers fell asleep, how long it took them to fall asleep, the total amount of sleep, and the type of sleep obtained.

Polysomnography (PSG) involves the continuous measurement of physiological variables that are used to distinguish the states and stages of sleep (refs. 24, 25). Standard sleep-laboratory-based PSG for differentiation of sleep and wakefulness involves recording brain waves activity (electroencephalogram or EEG), eye movements (electrooculogram or EOG), and muscle activity (electromyogram or EMG). These physiological variables allow the differentiation of sleep and wakefulness and the two distinct states of sleep: NREM (pronounced non-REM) and REM (rapid-eye-movement). NREM sleep is further divided into four stages with stages 1 and 2 being lighter sleep and stages 3 and 4 deeper sleep (slow-wave sleep). REM sleep is characterized by high brain activity, bursts of rapid-eye-movements, and muscle suppression; it is associated with dreaming. NREM and REM occur in a regular cycle throughout sleep.

In this study, only noninvasive procedures were used for attaching electrodes to the scalp and face of the test subjects to record these physiological variables. Brain activity was recorded from central positions on the scalp (C₃/A₂ and C₄/A₁) and eye movements were recorded from placements on the outside of the eyes (outer canthi) (ROC/A₁ and LOC/A₂). Muscle activity was not recorded in this study because (1) it can create artifacts (generated by talking, eating, etc.) that can obscure the recording; (2) the visibility of chin electrodes might have inhibited crewmembers from their usual movement outside the cockpit; and (3) although low muscle activity differentiates REM sleep, the rest period was considered too brief for the occurrence of REM. All of the PSG methods followed standardized and accepted procedures (refs. 24, 26).

These physiological variables were recorded during regular flight operations using an Oxford Medilog 9000-II ambulatory recorder (Oxford Medical Limited, Abingdon, Oxon, England). This small, lightweight (550-g), battery-operated system allowed continuous recording of brain and eye

movement activity onto a standard C-120 cassette tape. For this study, the physiological data from the planned 40 min. control period (RG) and control period (NRG) was played back through a polygraph to create a paper record, as if the data had been collected in a sleep laboratory. The 40 min. paper records for the RG control and NRG control periods were then visually scored according to standardized and accepted criteria (ref. 25).

Physiological Alertness/Sleepiness

If pilots obtained sleep during the rest period, how would this nap affect subsequent physiological alertness? There is a laboratory-based test, now widely used for the objective quantification of physiological sleepiness (i.e., the Multiple Sleep Latency Test or MSLT) (ref. 27). The laboratory provides a controlled and standardized environment to unmask underlying physiological sleepiness as measured objectively by the speed of falling asleep. However, there is an increasing interest in measuring physiological sleepiness in ambulatory individuals during regular operations (e.g., shift workers, train operators, truck drivers, and pilots) (for a discussion of this issue, see refs. 28-30). This requirement obviously presents a different set of circumstances than the laboratory environment and the use of some alternative approaches (e.g., portable physiological recorders).

Brain (EEG) and eye movement (EOG) activity can reflect the subtle ways that physiological alertness fluctuates. It is often difficult to discriminate and subjectively report these subtle physiological changes, though they can be measured, quantified, and related to performance. There have been a number of studies examining physiological sleepiness with measures of EEG and EOG activity in a variety of operational settings; some examples are train operators (refs. 31, 32); car drivers (refs. 33); shift workers (refs. 34, 35); and military operations (ref. 36). Also, several approaches have been used to analyze the EEG and EOG data, including automatic/computer methods (e.g., period-amplitude analysis or spectral analysis; for examples see refs. 37, 38) and visual evaluation (e.g., ref. 36).

These studies, and others, have generally found that three variables emerge that are associated with physiological alertness/sleepiness: alpha (8-12 Hz) and theta (3-7 Hz) EEG activity and SEMs in the EOG (refs. 28, 30, 37, 38). EEG alpha activity is considered quiet, relaxed wakefulness with eyes closed, appearing just prior to sleep onset and usually blocked when the eyes are opened (refs. 24, 25). EEG theta activity is acknowledged as light sleep, NREM stage 1 (refs. 24, 25). Slow-rolling eye movements (SEMs) are associated with the transition to sleep and may reflect the perceptual disengagement from the environment that characterizes sleep onset (refs. 24, 25).

Torsvall and Akerstedt provide one example of how these variables have been related to physiological sleepiness in active individuals (ref. 3). Using Medilog recorders, EEG and EOG data were collected during a monotonous 45 min. visual vigilance task. Spectral quantification of the EEG demonstrated clear, homogeneous patterns related to accurate performance, errors, and periods of "dozing off" (considered extreme behavioral sleepiness). EEG power density in the alpha, theta, and delta bands was highest just before dozing off periods and lowest during "hits" (i.e., accurate performance). The alpha power increased by a factor of 6, and theta power increased by a factor of 3, from scoring a hit to dozing off. The occurrence of SEMs also increased significantly before dozing off and was associated with decreased performance. This laboratory-controlled study of active individuals demonstrated that there was a relationship between physiological sleepiness and behavioral performance reflected in systematic changes in EEG and EOG activity. Therefore, quantification of EEG frequency and EOG changes associated with increased physiological sleepiness may identify periods of vulnerability when there is an increased risk of lapses in vigilance and performance, possibly without subjective awareness. These brief and subtle changes in brain and eye activity are especially important in light of previous data that suggest that the subjective reports by pilots of alertness/sleepiness are poorly related to their level of physiological sleepiness (refs. 39, 40).

Returning to the question originally posed: If the pilots were able to sleep during the rest period, was this nap associated with the subsequent maintenance or improvement in physiological alertness? The Medilog recorder provided continuous EEG and EOG data that were examined for changes related to physiological alertness during critical phases of operation. The initial analysis

focused on the period 1 hr. before top of descent (TOD) through descent and landing. This represented about the last 90 min. of flight. A microevent analysis of this 90 min. period identified specific EEG and EOG changes that occurred at anytime during this period. Based on the scientific research previously cited, the individual occurrences of three specific physiological events associated with increased sleepiness were scored: (1) EEG alpha activity (8-12 Hz), (2) EEG theta activity (3-7 Hz), and (3) EOG slow-rolling eye movements (SEMs; > 100 μ V amplitude, > 1-sec. duration) (refs. 24, 28, 29).

The duration of each microevent occurrence was scored according to these three time bins: (1) 5-10 sec., (2) 11-15 sec., and (3) >15 sec. The events were analyzed visually on a screen by a research assistant with over 6 years experience scoring sleep. Subsequent analyses are planned to compare visual scoring of microevents to spectral analysis and to examine other phases of flight.

The term "microsleep" is often used to describe the brief occurrence of EEG theta activity that can be associated with a performance lapse (e.g., ref. 6). However, as indicated by the scientific literature previously described, EEG alpha and SEMs also increase significantly before and during performance lapses. Therefore, the term adopted for the approach described here was "microevent." These EEG (alpha and theta) and EOG (SEMs) microevents are associated with physiological sleepiness and have been related to decreased behavioral performance (see previous citations). Relative to the use of the more popular term, microsleep, microevents reflect arousal transitions and attention lability (e.g., eye closures) rather than states per se. Therefore, this intensive analysis identified the occurrence of EEG and EOG microevents, lasting 5 sec. or longer, associated with increased physiological sleepiness during the last 90 min. of flight for both the NRG and RG.

Another physiological measure of pilot sleepiness was determined from the rest period data. Physiological sleepiness (sleep tendency) has been operationally defined as the speed of falling asleep, that is, a sleepy individual falls asleep quickly (short sleep latency) and alert individuals take a long time to fall asleep or do not fall asleep (long sleep latency) (refs. 21, 27). Therefore, not only is the occurrence of sleep during the rest period important, but the speed at which crewmembers fall asleep can be used as an indication of their level of physiological sleepiness.

On initial data collection trials, when standard Medilog 9000 recorders were used in the cockpit, a 10 Hz noise was recorded that obscured the biological signals. Avoiding all the potential sources of electrical noise in the cockpit appeared impossible, and an internal 10 Hz filter would have removed EEG frequencies crucial to the determination of sleep and wakefulness. Systematic troubleshooting procedures demonstrated that the interference was created by 400 Hz electrical activity prevalent in the cockpit and that it resulted in an "aliased" 10 Hz activity. A new Medilog 9000-II recorder, superseding the 9000, was available with improved common mode-rejection and enhanced screen drive frequencies up to the 400 Hz range. Oxford engineers modified the 9000-II further with input filters configured for 40 dB rejection of 400 Hz that provided a bandwidth of 0.5 to 40 Hz. The modifications of the 9000-II resulted in artifact-free physiological recordings in the cockpit environment (ref. 41).

A portable sleep laboratory was created with all the necessary equipment and supplies to conduct the ambulatory physiological recordings with the Medilog 9000-II recorders. During the data collection trips, the NASA research team organized the equipment and supplies in one hotel room where the electrode application took place before departure for the airport. Most electrodes were applied in the hotel room, especially those that required chemicals not allowed on the flight deck. The leads were bundled up and placed on the top of the head underneath the uniform hat to minimize the reactions of others. Generally, the hook-up procedure required about 12-15 min. per pilot to complete. Once on the flight deck, the remaining electrodes were placed and the physiological recording initiated. Once the recordings were initiated, the Medilog was stored in the pocket on the back of each pilot's seat. When leaving the cockpit, the pilot would usually wear a uniform hat, sometimes a jacket, and use a shoulder strap to carry the Medilog. The physiological recordings were continued throughout the flight. After landing and postflight duties, all of the electrodes, except the EEG scalp placements, were removed in the cockpit. The last EEG electrodes were removed at the layover hotel.

3.5.2 Performance: Sustained Attention/Reaction Time

In humans, performance probes are commonly used to evaluate the functional capability of persons who are either experiencing sleep loss or who are suspected of having occupationally induced fatigue due to their work-rest schedules. These tasks are an essential means for obtaining an estimate of best effort over time. When used in field studies, they provide an index of the severity of functional impairment present during a field trial without taking the costly approach of using more dramatic or very infrequent field outcome variables (e.g., crashes or near misses). Thus, performance probes serve to: (1) identify zones of vulnerability in sleepy and fatigued persons; (2) provide a common metric by which field data can be calibrated against laboratory data; and (3) give meaning to the consequences of physiological and subjective changes in flight crews.

There is ample evidence that fatigue resulting from sleep loss, acute or chronic, as well as circadian rhythm disturbance results in diminished performance capability (refs. 2, 6, 42-46). The performance test selected for this field experiment had to meet four major criteria:

1. Since the primary hypothesis of the experiment was that planned cockpit rest would diminish the effects of fatigue in long-haul crews, the task had to be well documented in laboratory studies of sleep loss, napping, and circadian rhythms to be sensitive even to subtle shifts in sleepiness/alertness.
2. The task had to reflect variability caused by sleepiness in a basic human performance capability, such as attention, which is a fundamental feature of cognitive and flight operations tasks.
3. Since the experiment required repeated performance measurements before, during, and following flight operations, a task was required that could be carried out at each time point, rather than only during flight or only pre- and postflight. This repeated assessment meant that the performance probe also had to be generally devoid of practice or learning effects.
4. The performance task selected had to be sufficiently brief to avoid interfering with actual flight operations and routine pre- and postflight activities (i.e., the real-world scenario), yet it had to yield performance parameters that clearly were informative about the nature of the change in the central nervous system (CNS) associated with fatigue due to sleep loss, circadian rhythm disturbance, and night flights.

Given these criteria, a highly reliable and well-validated performance probe was selected over an approach that relied on flight operations parameters or that utilized complex cognitive tasks. The former was rejected because there is as yet no reliable scientific data base on the extent to which fatigue alters performance of specific flight operations tasks. In addition, among other problems of standardization in a field study, operations tasks can only be measured during flights in actual real world scenarios (not pre- or postflight). Hence, the use of flight-operations tasks in this experiment was neither preferred nor practical, despite their face validity. The repeated-measures nature of the design also precluded the use of many complex cognitive tasks (based on laboratory research), which are subject to major secondary variance from practice effects (intrasubject variability) and individual differences (intersubject variability).

The performance probe chosen for this study was a psychomotor vigilance task (PVT) that requires sustained attention and rapid reaction time to an intermittent light stimulus for a 10 min. period. It meets the four major criteria listed above, and attentional capacity as assessed by this task is operationally significant, since attention is fundamental to many tasks and most information exchange. Moreover, there are extensive data showing that high-signal-load reaction time tests are sensitive to total sleep loss (refs. 13, 47-53), to partial sleep loss (refs. 54, 55), and to circadian variation in performance efficiency (refs. 56, 57).

PVT data were recorded as sine waves on an audio tape in a portable device that consists of a modified, battery-powered cassette player (9 by 4 by 2 inches). It had a light-emitting diode (LED) counter window next to a small, white microswitch button on the face of the recorder. A stimulus, red digits "000," appeared in the window and began increasing in milliseconds. The pilot sat with the PVT positioned comfortably in his or her lap, finger poised on the push button, and watched

the blank window. The pilot was instructed to push down on the button as soon as the stimulus lights appeared, with an emphasis on the speed of response. When the button was pressed, the running millisecond counter stopped and revealed the response time. The number was displayed for 1.5 sec., then the display went blank and there was a variable, 1-to-10-sec. interval before the onset of the next stimulus. Each pilot completed the PVT five times over the course of each study flight leg. Each trial was administered for 10 min.: (1) preflight in the hotel; (2) after top of climb and before the scheduled rest or control period; (3) closely following the identified rest or control period; (4) just before TOD; and (5) postflight in the hotel.

Over the past 10 years, Dinges focused on the precise nature of performance impairment engendered by sleep loss and shifts in work-rest schedules (refs. 6, 58). Using reaction time as the basic response mode, Dinges has developed a data processing system of sustained attention on the PVT that is very sensitive to fatigue resulting from sleep loss, as well as to circadian variation and desynchronization. These methods go beyond the usual analytical approaches applied to reaction time and sustained attention tasks (ref. 59). The completed cassette data tapes were analyzed by the University of Pennsylvania laboratory. Data reduction through the software system resulted in four measures of performance for each 10 min. PVT trial: (1) response slowing (median reaction time [RT] in a trial); (2) response lapsing (mean of the slowest 10% RTs in a trial); (3) optimum responding (mean of the fastest 10% RTs in a trial); and (4) vigilance decrement (slope and y-intercept of a least-squares regression equation fitted to the 1 min. changes across the 10 min. trial) (refs. 13, 50, 59, 60). Using this analytical approach, the PVT has been found to be more sensitive to sleep loss, circadian phase, and the beneficial effects of naps on alertness, than an array of short-duration cognitive tests that are typically used in laboratory studies of circadian rhythms (ref. 12).

3.5.3 Actigraphy: Motor/Physical Activity

Actigraphy is a relatively new ambulatory technique that uses a device to objectively record circadian rest/activity patterns over many days (refs. 61, 62). The actigraph provides information that complements physiological data and subjective self-report measures. It is a cost-effective means for collecting continuous, objective behavioral data in operational settings without interfering with the subject's usual activity.

The actigraph device (wrist activity monitor or WAM) used in this study was a lightweight (3 oz) microprocessor with an internal piezoelectric sensor, housed in a small rectangular box (6 by 4 by 1.5 cm) that straps to the nondominant wrist (Ambulatory Monitoring; Inc., Ardsley, New York). The unit has no external wires and can be comfortably worn for many days (removed only for bathing). The actigraph stores the number of movements recorded by the piezoelectric sensor into discrete bins. The time-base can be preset from 7 sec. to 20 min.; with the smaller bin length, the device will continuously record data for less total time before filling its memory. In this study, a 2 min. bin length allowed continuous data collection for 16 days. By use of an interface device, the data were transferred from the actigraph to a microcomputer as an ASCII file. The file contained the day and time (to the minute) of each consecutive bin, as well as the number of movements accumulated in each bin. Both a histogram printout of the record and a numerical printout were derived. Computer analysis of the actigraph data yielded information relevant to the temporal placement of sleep periods, to the amount of wake activity, the duration of sleep periods on layover, and the amount of movement during sleep.

A WAM was sent to all volunteers before they left home. It was worn continuously 3 days before leaving home, throughout the entire 12-day trip schedule, and for up to 3 days after arriving home.

3.5.4 Logbook

The NASA Fatigue Countermeasures Program has accumulated extensive experience with a Pilot's Daily Logbook to collect subjective, self-report data in a variety of studies (for examples, see refs. 3, 36). The logbook is divided into two basic sections: (1) a daily log and (2) a mood

checklist. The daily log provides space for recording wake-up time, sleep patterns and quality, exercise, duty time, layovers, naps, meals and beverages, smoking behavior, medication use, and physical symptoms. Included is a 10 cm analog scale where pilots subjectively rate their level of waking alertness from most drowsy to most alert. The mood checklist contains 26 adjectives that are rated from 0 = not at all to 4 = extremely. The Pilot's Daily Log provides information on 24 hr. patterns of activity, layover sleep, daily food intake, etc., to give an overall record of a pilot's activities on a trip.

The Pilot's Daily Log was sent to all volunteers before they left home. It was completed continuously, on a daily basis, 3 days before leaving home, throughout the entire 12-day trip schedule, and for 3 days after arriving home.

3.5.5 Subjective Mood/Alertness Ratings

The same 10 cm analog alertness scale and the 26-item mood checklist in the Pilot's Daily Log were to be completed and administered hourly during each study flight leg. This checklist contained self-report adjectives to characterize mood and alertness.

3.5.6 Observer's Log

One member of the NASA research team (usually an individual holding at least a private pilot license) maintained an Observer's Log throughout each study flight leg. This log was used to record information on flight activities and conditions, such as turbulence, lighting, block and flight times, takeoff and landing events, equipment problems, meals, and other noteworthy occurrences during flights. Also, the NASA research team maintained a time-line during each study flight leg to document when study procedures actually occurred and to record the flow of the protocol.

3.5.7 Operational Problem

A gross-weight takeoff problem was administered immediately following the identified nap or control period. It was intended to provide information on cognitive functioning and the potential effects of sleep inertia (intense sleepiness experienced following an awakening from deep sleep) after the nap.

3.5.8 NASA Background Questionnaire

The NASA Background Questionnaire was designed in June 1982 for use in studies of human performance in long- and short-haul flight operations (ref. 63). It contains 215 questions in a variety of formats and usually takes less than 1 hr. to complete. The inventory examines some of the factors involved in pilot fatigue, including (as stated in the instructions to pilot participants) sleep-rest cycles, nutrition, life-style, attitudes toward work, and certain personality profiles. Sections of the inventory assess the following: basic demographics, including flight experience; general health status and activities; home sleep quantity, quality, and timing; and self-ratings of personal characteristics.

The background questionnaire was sent to pilot volunteers as part of the initial information packet prior to field data collection. It was completed and returned to the NASA research team that accompanied the crew during the study flight legs.

3.6 Procedures

To initiate the field data collection component of the study, volunteer pilots were met by the NASA research team in Honolulu the day before the first study-trip leg. It was at this time that the crews were informed about their random placement into either the no-rest control group or the rest group. No information prior to this time indicated whether a crew would be allowed the rest opportunity. This was done to minimize any alterations of pilots' usual trip activities, sleep/wake schedule, etc., before the study legs. An orientation meeting with the crewmembers was used to describe the physiological recording procedures, demonstrate the PVT and other study measures, discuss specifics of the protocol, and answer any questions.

The overall cockpit rest protocol is shown in figure 3. The first line shows the general period of study, including days at home, flights, and home post-trip. The second line portrays the time-line for the protocol during each study flight. It indicates the placement of the three rest periods in the middle portion of the flight. Finally, the third line provides a more detailed view of the approximately 60 min. identified as the planned rest/control period.

3.6.1 Cockpit Rest Guidelines

The following guidelines were used for all cockpit rest opportunities. They were established as a first attempt to structure procedures for planned cockpit rest periods.

1. Soon after top of climb (TOC), a specific rest period (see fig. 3: rest period a, b, or c) was chosen by each crewmember. This constitutes a major aspect of the nap: it was planned and each crewmember knew generally when a rest opportunity would occur. The landing pilot had first choice, the nonlanding pilot had second choice, and the flight engineer had third choice. As part of the study, the captains agreed that the landing pilot would have priority for choice of rest period.
2. The rest periods were scheduled during cruise overwater, which is a low-workload phase of flight.
3. The rest periods were scheduled for three consecutive 1 hr. periods during cruise.
4. One crewmember was scheduled to rest at a time while the other pilots maintained flight operations. The other crewmembers rotated on the prearranged schedule.
5. The actual rest opportunity was divided into three phases: (1) a 3 min. preparation, which involved any debriefing, completion of tasks in progress, getting comfortable in the cockpit seat, etc.; (2) a 40 min. rest opportunity (pilots were offered the use of eye shades, ear plugs, and an inflatable neck pillow); (3) a 20 min. recovery period used to administer performance tests, obtain subjective ratings, etc., and to allow a return to full alertness before re-entering the operational loop.
6. Access to the cockpit was restricted during rest periods to minimize interruptions. Other crewmembers attempted to be quiet and not disruptive.
7. Rest was terminated at a predetermined time by a researcher.
8. Before resuming flight duties, the rested crewmember was briefed by the other crewmembers on flight status and any relevant flight information.

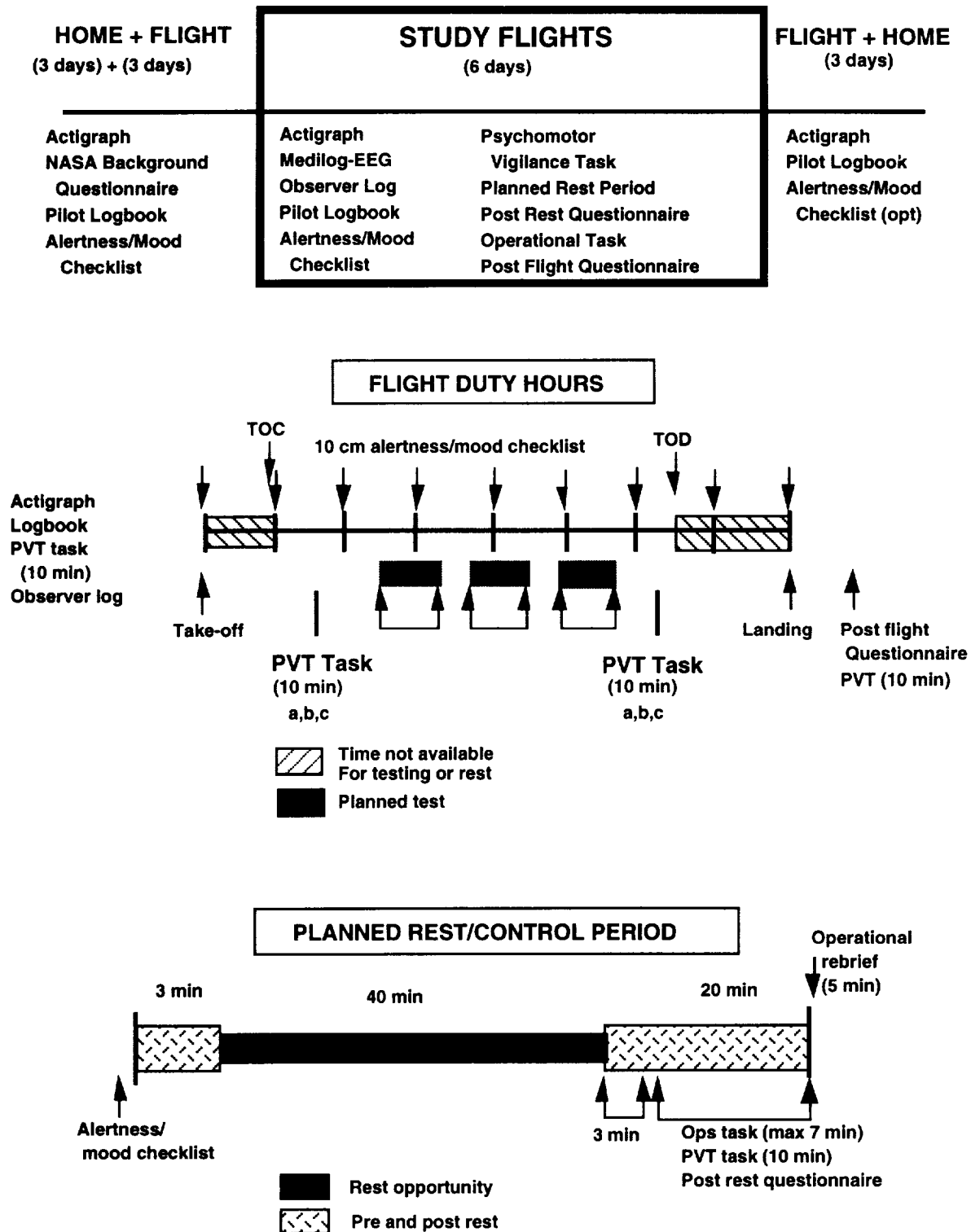


Figure 3. Overall cockpit rest study protocol.

3.6.2 Safety Procedures

The following cockpit rest period safety procedures were followed to minimize any interference with the safe operation of the aircraft.

1. Two crewmembers and two NASA observers were available while any one crewmember was resting.
2. The 20 min. recovery period was intended to allow sufficient time to return to full alertness and evaluate any concerns before re-entering the operational loop.
3. The potential for sleep inertia that might decrease performance was assessed (through inquiry by the NASA observers) before resuming flight duties.
4. A postrest update was provided on flight status and other relevant operational information before resuming flight duties.
5. The captain was to be alerted immediately upon first indication of any potential anomaly.
6. All rest periods were scheduled for completion at least 1 hr. before descent.
7. Safe, normal operation of aircraft was acknowledged as the highest priority, of course, and study procedures were not be permitted to interfere.

3.6.3 No-Rest/Control Group Procedures

Soon after TOC, the volunteer pilots in the NRG also identified a specific control period during the cruise portion of flight (see fig. 3: position a, b, or c). This served as a control period, and they followed the same procedures with a preparation time, 40 min. test period, and 20 min. “recovery” period when performance tests were administered. However, during the identified 40 min. control period, NRG pilots were instructed to continue their usual flight activities.

4.0 RESULTS

4.1 Subject Characteristics

Subject volunteer crews were randomly assigned to one of the two study groups. The NRG consisted of three crews totaling nine subjects. The RG consisted of four crews totaling 12 subjects. The mean age, mean years of experience, and sex of the volunteers are given in table 2. All of these factors were comparable between the two groups. One other field data collection trip, not included in this data set, was begun and then discontinued when rescheduling caused an alteration in the study trip schedule.

4.2 Pilot Choice of Rest Position

The procedures provided first choice of rest position to the landing pilot. Figure 4 shows the landing pilots’ (for both captains and first officers [FOs]) choices for rest position a, b, or c and also the nonlanding pilots’ choices. The main finding was that both captains and FOs generally chose the last rest position when they were landing the aircraft and rarely chose the first rest position. This result suggests that rather than rest early in the flight, when pilots may still be alert from layover sleep, the preferred strategy was to use the rest position later in the flight and closer to the landing.

Table 2. Final study population subject characteristics

	Sample size	Age (mean)	Experience (mean yr.)	Sex
No-rest group	9	38.8	15.2	9M
Captain	3	52.0	25.7	3M
FO	3	40.7	15.7	3M
SO	3	33.7	4.2	3M
Rest group	12	38.7	13.4	11M 1F
Captain	4	50.3	25.3	4M
FO	4	31.8	11.5	3M 1F
SO	4	34.0	3.5	4M
Total	21	41.6	14.2	20M 1F

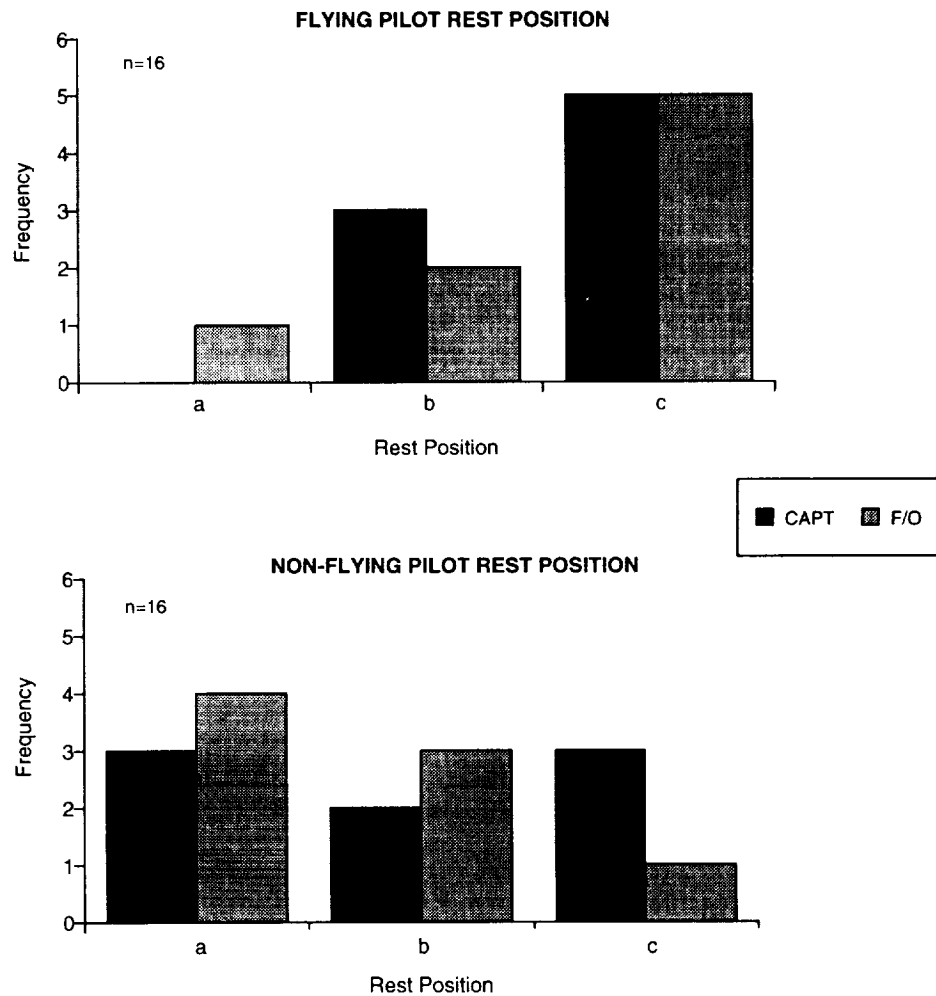


Figure 4. Choice of position for cockpit rest by landing vs. nonlanding pilot and captain vs. FO. (Landing pilot received first choice.)

4.3 Rest Period Sleep: EEG Findings

There were 12 subjects in the RG, each flying four segments, for a total of 48 rest periods. Physiological data were lost on three of these flight legs owing to a variety of factors. In view of the technical nature of the physiological recordings and the complexity of the operational environment in which the data were collected, a 6% data loss was considered minimal and acceptable.

First, the total number of sleep episodes that occurred is described. These data were then analyzed for six factors that describe the quantity and quality of sleep. These factors include the total amount of sleep (total sleep time), the sleep efficiency (total sleep time divided by the 40 min. rest period opportunity), the time to fall asleep (sleep latency), and the percentage of NREM sleep stages 1, 2, and slow-wave sleep. Each of these six factors was analyzed for overall descriptive summaries and also for (1) effects across study legs; (2) first-half study legs (study legs 1 and 2) vs. second-half study legs (study legs 3 and 4); (3) day (study legs 1 and 3) vs. night (study legs 2 and 4) leg differences; and (4) differences by flight position (captain vs. FO vs. SO).

The analyses for each of these six factors will be described in the text, with the significant findings highlighted graphically.

4.3.1 Total EEG Sleep Episodes

On 93% (42 out of 45) of the rest-period opportunities available for analysis, the RG subjects were able to sleep. There were three subjects who did not sleep on one flight leg each. One FO and one SO obtained no sleep on their fourth flight leg and one FO had no sleep on his third flight leg. All three of these subjects were able to sleep on the other three flight legs of their trips. A more detailed examination of these subjects will be presented later.

Two main analytical approaches were performed to examine the quantity and quality of sleep obtained during the planned rest period. First, the 42 rest periods in which sleep occurred were analyzed. The three no-sleep rest periods were not included in these analyses, for they would have artificially introduced an increased variability into the data set and potentially obscured meaningful results or suggested spurious findings.

In consideration of the potential sensitivity of these data, an even more conservative approach was used. The second analysis was conducted on the data from the six subjects, 24 rest periods, with complete physiological data. (Overall, three subjects had missing data due to equipment malfunctions and three subjects had one rest period with no sleep.) Statistical comparisons were conducted using analysis of variance. Those subjects for whom complete physiological data were obtained provided the most comprehensive representation of the physiological sleep that occurred across study flight legs. The importance of intersubject variability can be assessed in this data set.

Therefore, the RG (42) analysis represents the means and standard deviations for the 42 rest periods in which sleep occurred. The second analysis, RG (24), is the conservative ANOVA statistical comparisons based on the 24 rest periods that represent the six subjects with complete physiological data.

4.3.2 Total Sleep Time

The total sleep time was calculated as the total amount of sleep (in minutes) from sleep onset (defined as 1.5 min. of continuous sleep) until the final awakening. For the RG (42), the average total sleep obtained per rest period was 25.78 min. (SD = 9.58 min.). For the RG (24), the average total sleep obtained per rest period was 28.45 min. (SD = 6.28). Statistical analyses demonstrated that there were no significant differences related to trip legs (table 3), halves of the trip (table 4), day versus night flights (table 5), or by flight position (table 6). Overall, no significant findings emerged related to the average total sleep time.

Table 3. Average total sleep time by trip leg (min.)

	Leg 1	Leg 2	Leg 3	Leg 4	F	p
RG (42)	26.76 (9.85)	28.24 (9.53)	19.12 (10.01)	28.89 (5.91)	2.44	.08
RG (24)	29.97 (7.46)	29.57 (6.21)	22.43 (4.59)	31.82 (2.20)	2.91	.07

Table 4. Average total sleep time by trip half (min.)

	First trip half	Second trip half	F	p
RG (42)	27.70 (7.59)	21.73 (10.11)	3.30	.10
RG (24)	29.77 (4.16)	27.13 (2.65)	1.24	.32

Table 5. Average total sleep time by day vs. night (min.)

	Day flights	Night flights	F	p
RG (42)	23.29 (7.31)	27.37 (7.83)	2.79	.12
RG (24)	26.20 (4.67)	30.69 (2.14)	3.18	.14

Table 6. Average total sleep time by flight position (min.)

	Captains	First officers	Second officers	F	p
RG (42)	27.35 (1.68)	25.70 (5.75)	22.96 (9.75)	.45	.65
RG (24)	27.42 (2.05)	28.98 (2.14)	29.73 (1.84)	.86	.61

4.3.3 Sleep Efficiency: Total Sleep Time/40-Minute Rest Period

Sleep efficiency is the amount of time during an identified period that an individual is actually asleep. This parameter can reflect prior sleep loss when it results in more consolidated sleep and a higher sleep efficiency than might usually be expected. In the circumstances of this study, it was calculated by dividing the total sleep time by the 40 min. allowed for the rest period. Therefore, if a crewmember had slept the entire 40 min., the sleep efficiency would have been 100%. Obviously, this metric parallels the total sleep time results, and findings were not expected to vary from these. It provided some information, however, regarding the percentage of the rest period time spent asleep.

For the RG (42), the average sleep efficiency per rest period was 64.47% (SD = 23.94). For the RG (24), the average sleep efficiency per rest period was 71.12% (SD = 15.67). Statistical analyses demonstrated that there were no significant differences related to trip legs (table 7), halves of the trip (table 8), day versus night flights (table 9), or by flight position (table 10). Overall, no

significant findings emerged related to the average sleep efficiency. As expected, this exactly parallels the total sleep time findings.

In a usual daytime nap, sleep efficiency would generally be in the 50%-55% range. Therefore, these results (64% and 71% sleep efficiency) may reflect accumulated sleep loss.

Table 7. Average total sleep efficiency by trip leg

	Leg 1	Leg 2	Leg 3	Leg 4	F	p
RG (42)	66.90%(24.59)	70.61%(23.84)	47.81% (25.00)	72.23% (14.76)	2.45	.08
RG (24)	74.95%(18.60)	73.90%(15.49)	56.10% (11.42)	79.52% (5.58)	2.91	.07

Table 8. Average total sleep efficiency by trip half

	First trip half	Second trip half	F	p
RG (42)	69.27%(18.96)	54.33% (25.27)	3.30	.10
RG (24)	74.43%(10.41)	67.81% (6.61)	1.24	.32

Table 9. Average total sleep efficiency by day vs. night

	Day flights	Night flights	F	p
RG (42)	58.22% (18.24)	68.45% (19.56)	2.81	.12
RG (24)	65.53% (11.63)	76.71% (5.31)	3.19	.13

Table 10. Average total sleep efficiency by flight position

	Captains	First officers	Second officers	F	p
RG (42)	68.39% (4.17)	64.29% (14.38)	57.40% (24.34)	.45	.65
RG (24)	68.54% (5.10)	72.48% (N=1)	74.30% (4.53)	.87	.50

4.3.4 Time to Fall Asleep: Sleep Latency

Sleep latency was defined as the time from the identified beginning of the 40 min. rest period to the first continuous 1.5 min. of sleep. For the RG (42), the average time to fall asleep per rest period was 5.55 min. (SD = 5.04 min.). For the RG (24), the average time to fall asleep per rest period was 4.10 min. (SD = 2.88 min.). Statistical analyses demonstrated that there were no significant differences related to trip legs (table 11), halves of the trip (table 12), day versus night flights (table 13), or by flight position (table 14). Overall, there were no significant findings related to the average sleep latency.

Table 11. Average sleep latency by trip leg (min.)

	Leg 1	Leg 2	Leg 3	Leg 4	F	p
RG (42)	4.52 (3.29)	3.97 (2.73)	7.96 (6.65)	6.16 (6.61)	1.37	.27
RG (24)	3.15 (2.48)	3.82 (2.89)	5.12 (3.25)	4.33 (3.26)	0.50	.69

Table 12. Average sleep latency by trip half (min.)

	First trip half	Second trip half	F	p
RG (42)	4.25 (2.98)	7.11 (6.51)	3.52	.07
RG (24)	3.48 (2.28)	4.73 (2.02)	1.20	.32

Table 13. Average sleep latency by day vs. night (min.)

	Day flights	Night flights	F	p
RG (42)	6.02 (4.41)	4.92 (3.49)	.62	.45
RG (24)	4.13 (2.01)	4.08 (2.71)	.002	.97

Table 14. Average sleep latency by flight position (min.)

	Captains	First officers	Second officers	F	p
RG (42)	5.83 (3.11)	4.42 (3.67)	7.10 (4.72)	0.48	.64
RG (24)	4.34 (1.11)	1.25 (N=1)	5.18 (0.71)	5.37	.10

4.3.5 Percent NREM Stage 1 Sleep

NREM stage 1 sleep is the lightest sleep stage. This metric portrayed the percentage of total sleep time spent in NREM stage 1 sleep and provided some indication of the depth of the sleep obtained. For the RG (42), the average NREM stage 1 percent per rest period was 30.28% (SD = 22.50). For the RG (24), the average NREM stage 1 percent per rest period was 24.75% (SD = 15.52). There was a significant effect related to trip legs (table 15), but there were no significant findings related to halves of the trip (table 16) or flight position (table 17).

Post hoc analyses of the RG(24) were performed to understand more fully the significant contribution by trip leg. Two significant post hoc comparisons emerged. The average NREM stage 1 sleep percent on leg 1 (23.10%) was significantly greater than the leg 4 (10.00%) average NREM stage 1 sleep percent ($F_{1,5} = 13.58$, $p = .01$) (A p value equal to .01 indicates that there is a 99% confidence that this is a significant finding due to trip leg and would only occur by chance 1 time in a 100). Also, the average NREM stage 1 sleep percent on leg 3 (37.00%) was significantly greater than the leg 4 (10.00%) average NREM stage 1 sleep percent ($F_{1,5} = 36.76$, $p = .002$).

The average NREM stage 1 sleep percent on the day legs (1 and 3) was significantly greater than the NREM stage 1 sleep percent on the last night leg (leg 4).

There was also a significant effect for average NREM stage 1 sleep percent related to day versus night flights (table 18). The average NREM stage 1 percent for day flights (legs 1 and 3) was greater than the average NREM stage 1 percent for night flights (legs 2 and 4). There was a significant effect for the RG (42) subjects and a similar statistical trend in the more conservative analysis for the RG (24) subjects.

Table 15. Average NREM stage 1 sleep percent by trip leg

	Leg 1	Leg 2	Leg 3	Leg 4	F	p
RG (42)	28.27%(15.61)	28.22%(20.79)	47.63% (29.58)	16.21%(11.19)	3.90	.02*
RG (24)	23.10%(11.37)	28.90%(19.17)	37.00% (10.99)	10.00% (5.04)	4.63	.02*

* $p < .05$.

Table 16. Average NREM stage 1 sleep percent by trip half

	First trip half	Second trip half	F	p
RG (42)	28.23% (9.80)	36.84% (30.29)	1.01	.34
RG (24)	26.00% (7.80)	23.50% (6.59)	0.56	.49

Table 17. Average NREM stage 1 sleep percent by flight position

	Captains	First officers	Second officers	F	p
RG (42)	24.25% (6.11)	28.50% (8.69)	40.85% (18.29)	1.99	.19
RG (24)	26.53% (4.98)	15.95% (N=1)	26.48% (5.80)	1.68	.32

Table 18. Average NREM stage 1 sleep percent by day vs. night

	Day flights	Night flights	F	p
RG (42)	37.30% (13.47)	25.32% (16.77)	8.00	.02*
RG (24)	30.05% (5.65)	19.45% (9.71)	6.04	.06

* $p < .05$.

4.3.6 Percent NREM Stage 2 Sleep

NREM stage 2 sleep is a deeper sleep stage than NREM stage 1. It is the predominant sleep stage during nocturnal sleep, comprising about 50% of total sleep time. This metric portrays the percentage of total sleep time spent in NREM stage 2 sleep. For the RG (42), the average NREM stage 2 percent per rest period was 61.65% (SD = 21.63). For the RG (24), the average NREM stage 2 percent per rest period was 67.30% (SD = 17.66). Statistical analyses demonstrated that there were no significant differences related to trip legs (table 19), halves of the trip (table 20), day

vs. night flights (table 21), or by flight position (table 22). Overall, no significant findings emerged related to the average NREM stage 2 percent.

Table 19. Average NREM stage 2 sleep percent by trip leg

	Leg 1	Leg 2	Leg 3	Leg 4	F	p
RG (42)	64.91% (13.94)	62.85% (19.22)	52.15% (29.32)	66.38% (23.37)	0.88	.46
RG (24)	66.30% (9.98)	70.22% (18.57)	63.00% (10.99)	69.67% (28.80)	0.38	.77

Table 20. Average NREM stage 2 sleep percent by trip half

	First trip half	Second trip half	F	p
RG (42)	64.27% (13.18)	55.00% (28.83)	1.13	.31
RG (24)	68.26% (13.71)	66.33% (17.19)	0.23	.65

Table 21. Average NREM stage 2 sleep percent by day vs. night

	Day flights	Night flights	F	p
RG (42)	58.44% (11.32)	63.13% (19.89)	0.99	.34
RG (24)	64.65% (7.29)	69.94% (23.27)	0.52	.50

Table 22. Average NREM stage 2 sleep percent by flight position

	Captains	First officers	Second officers	F	p
RG (42)	61.68% (12.70)	66.04% (12.59)	54.40% (16.97)	0.68	.53
RG (24)	64.03% (14.45)	83.62% (N=1)	64.04% (18.69)	0.63	.59

4.3.7 Percent NREM Slow-Wave Sleep

NREM slow-wave sleep is the deepest sleep. It is a combination of both NREM stages 3 and 4 and reflects the number of EEG delta waves. This metric portrays the percentage of total sleep time spent in NREM slow-wave sleep and provides some indication of the depth of the sleep obtained. For the RG (42), the average NREM slow-wave sleep percent per rest period was 8.07% (SD = 16.22). For the RG (24), the average NREM slow-wave sleep percent per rest period was 7.96% (SD = 18.01). There were no significant differences related to trip legs (table 23), halves of the trip (table 24), or flight position (table 25).

There was a significant effect for the average NREM slow-wave sleep percent for day versus night flights (table 26). The average NREM slow-wave sleep percent for day flights (legs 1 and 3) (4.3%) was less compared to the average NREM slow-wave sleep percent for night flights (legs 2 and 4) (11.6%).

Table 23. Average NREM slow-wave sleep percent by trip leg

	Leg 1	Leg 2	Leg 3	Leg 4	F	p
RG (42)	6.83% (12.10)	8.94% (16.48)	0.22% (0.70)	17.40% (25.07)	1.93	.14
RG (24)	10.62% (15.23)	0.88% (2.16)	0.00% (0.00)	20.33% (30.46)	2.47	.10

Table 24. Average NREM slow-wave sleep percent by trip half

	First trip half	Second trip half	F	p
RG (42)	7.51% (10.62)	8.15% (12.13)	0.05	.84
RG (24)	5.75% (7.31)	10.17% (15.23)	1.65	.26

Table 25. Average NREM slow-wave sleep percent by day vs. night

	Day flights	Night flights	F	p
RG (42)	4.27% (7.24)	11.56% (14.05)	7.57	.02*
RG (24)	5.31% (7.61)	10.61% (15.02)	2.51	.17

* $p < .05$.

Table 26. Average NREM slow-wave sleep percent by flight position

	Captains	First officers	Second officers	F	p
RG (42)	14.08% (14.69)	5.46% (6.40)	4.74% (9.23)	0.95	.42
RG (24)	9.46% (13.99)	0.43% (N=1)	9.48% (12.87)	0.18	.84

Thus, there was one significant finding that emerged for these factors. As a group, crewmembers had a higher percentage of NREM slow-wave sleep during night flights than on day flights. This suggests that deeper sleep occurred on night flights than on day flights.

Figure 5 presents the NREM stage 1, stage 2, and slow-wave sleep percentages of total sleep time for day versus night flights. This portrays the day flights with more light sleep and less deep sleep and the night flights with less light sleep and more deep sleep.

No REM sleep was observed in any of the rest period sleep episodes.

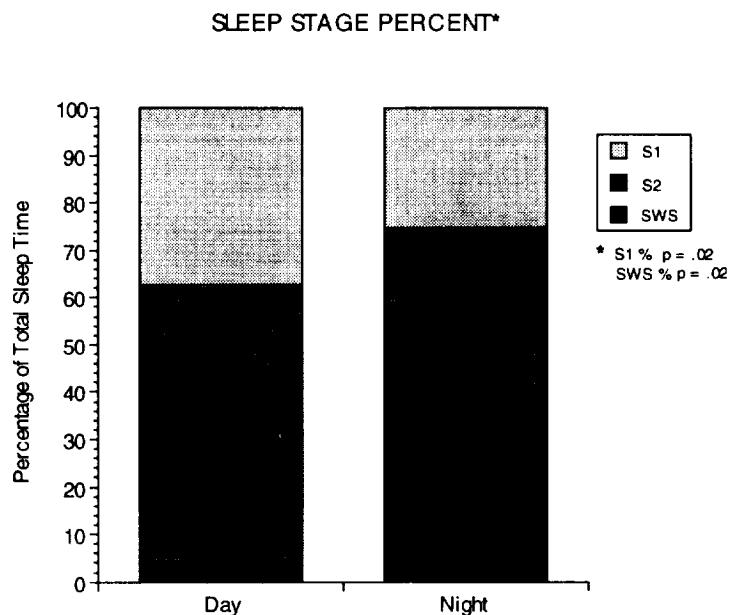


Figure 5. Percentage of total sleep time in stage 1, stage 2, and slow-wave sleep, by day vs. night flights.

4.3.8 RG Subjects With No Sleep

As indicated previously, there were three pilots who did not sleep on three separate rest period opportunities. Figure 6 portrays the sleep obtained on the other three legs of their trip schedules for these subjects. Each column indicates the total amount of sleep, composed of the total stage 1 sleep (TS1), total stage 2 sleep (TS2), and total slow-wave sleep (TSWS). Several points can be noted from these data. First, all three of the no-sleep episodes occurred later in a trip, with two of three on the fourth leg. Examination of the figure suggests that one FO and one SO generally slept below the RG average amounts. In particular, the SO demonstrated a relatively poor ability to obtain sleep on all but the first trip leg. These patterns and the subjects' inability to sleep on these three occasions highlight the complexity of this situation. There are a variety of factors that may have played a role in their inability to sleep, for example, individual differences, personality characteristics, circadian factors, or different sleep patterns. It is important to note that these individuals were able to obtain sleep on all other flight legs. A more detailed examination of factors that may have led to these no-sleep episodes is planned.

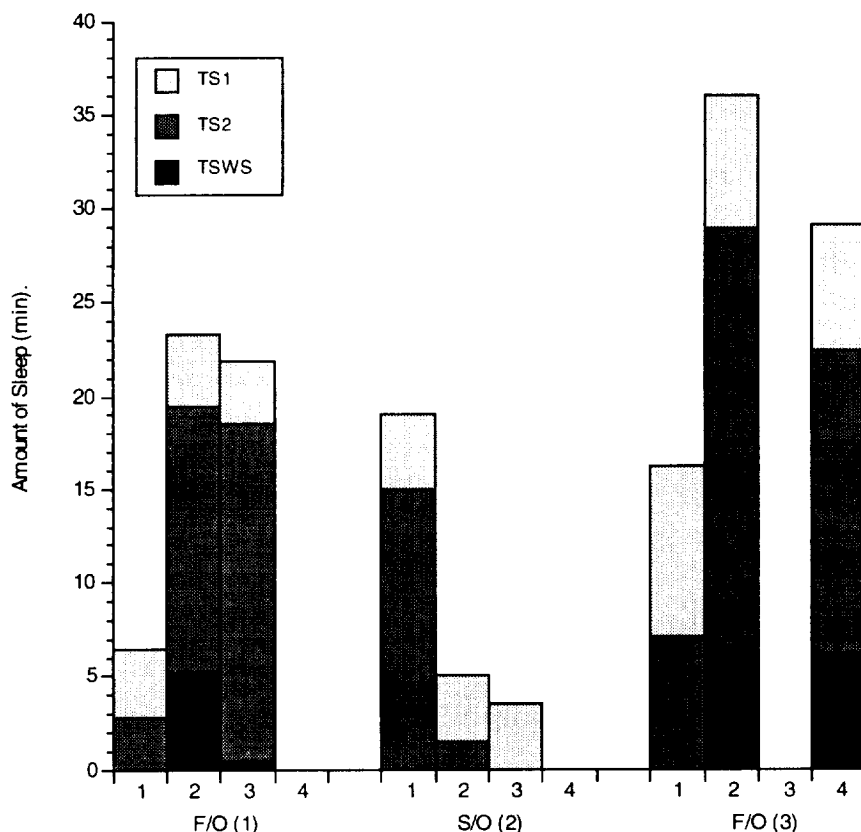


Figure 6. Percentage of total sleep time in stage 1, stage 2, and slow-wave sleep, for each of the three subjects in RG who did not sleep on one of the four trip legs; data given for the three legs that did include sleep.

4.3.9 NRG Subjects With Sleep During the Control Period

An interesting finding emerged from examination of the control period in the NRG subjects. This group underwent the exact same measurement and performance evaluation procedures as the RG; however, during the pre-identified control period, the NRG subjects were instructed to conduct their usual flight activities. Analysis of the EEG recordings for the 40 min. control periods for the NRG demonstrated that four NRG subjects fell asleep on a total of five occasions (one subject fell asleep during two different control periods). Four of the nine NRG subjects (44%) had at least one episode of spontaneous sleep during the control period. The total sleep (in minutes) for the five episodes is shown in figure 7. Although there were a couple of brief sleep episodes, two of the periods were over 10 min. long. Only NREM stage 1 and NREM stage 2 sleep occurred during these episodes; there was no deep NREM slow-wave or REM sleep.

4.4 Psychomotor Vigilance Task Performance

The 21 crewmembers who participated in the study each performed between 180 and 190 min. of the psychomotor vigilance task (PVT), for a total of 63 hr. of performance assessment (over 26,000 reaction times). For all four flight legs of the study, a 10 min. PVT trial was administered 1-2 hr. before each flight (preflight trial) and three times during the cruise portion of each flight (in-flight trial 1 was before the rest or control period, in-flight trial 2 was immediately after the rest or control period, in-flight trial 3 was before TOD). The PVT was also administered 1-2 hr.

following each flight (postflight), with the exception of study flight leg 4 (NRT to LAX) due to logistical problems. For this reason, analysis of PVT data was conducted in two basic ways. First, a 2 by 4 by 4 (rest/control conditions x study flight legs 1, 2, 3, 4 x preflight trial and in-flight trials 1, 2, 3) mixed-model analysis of variance (ANOVA) was conducted on each performance parameter. Second, a separate two-way mixed model ANOVA was carried out within each flight leg, utilizing the postflight trial on all but the fourth leg.

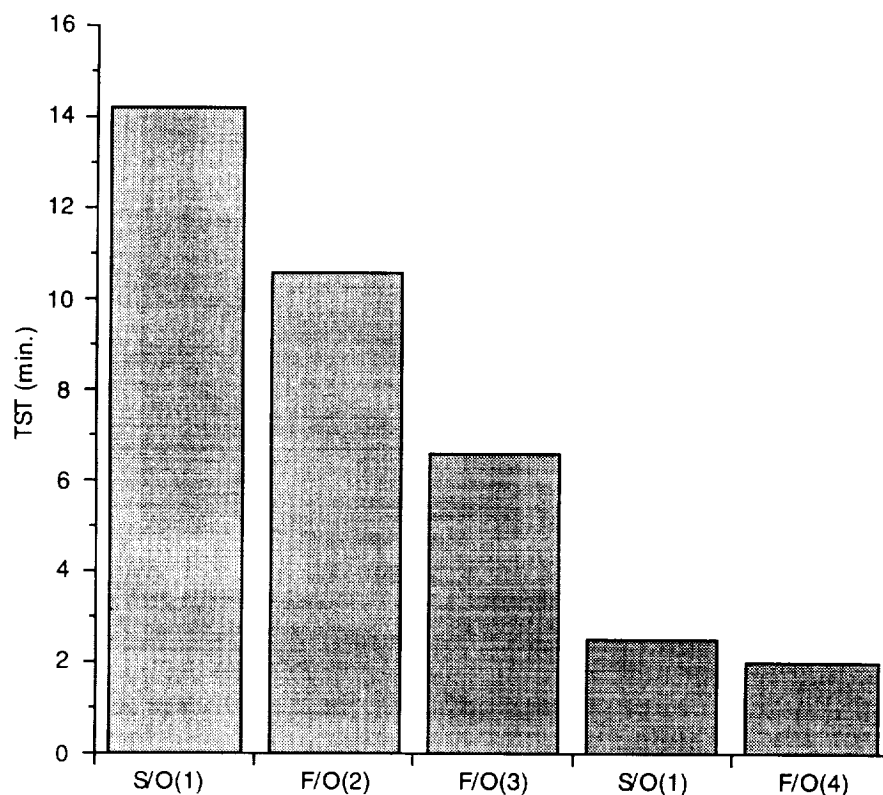


Figure 7. Total sleep time for the four NRG control subjects who fell asleep (for a total of five sleep episodes) during the 40 min. test period.

As described previously, the PVT data were analyzed for response slowing (median reaction time), lapse frequency, lapse duration, optimum response time, and vigilance decrement. Rather than review all of the PVT data, results for the median reaction time (response slowing), lapse frequency, and vigilance decrement are presented here. The results from the lapse duration and optimum response time provide similar findings and are presented in the appendix.

4.4.1 PVT Response Slowing (Median Reaction Time)

A characteristic feature of fatigue is the slowing of response output on cognitive tasks (ref. 6). Response slowing across PVT trials was assessed by determining the median reaction time (RT) per trial, to prevent a disproportionate influence from long-duration lapses. (For a discussion of increased performance variability caused by sleep loss, and the statistical approach to handle this variability, see ref. 58). Figure 8 shows the average of median RTs for the no-rest and rest groups for each trial of each study flight leg. The NRG displays far greater range of average responses across flight legs and trials than the RG, with response slowing especially evident on the third in-flight performance trial on study flight legs 2 and 4. The three-way ANOVA confirmed this observation. There were significant main effects for condition ($F_{1,19} = 9.19, p < .007$), flight leg

($F_{3,57} = 5.18, p < .003$), and trial ($F_{3,57} = 12.93, p < .0005$). There were significant interactions for condition by flight leg ($F_{3,57} = 3.38, p < .025$), and condition by trial ($F_{3,57} = 5.17, p < .003$), as well as for flight leg by trial ($F_{9,171} = 4.90, p < .0005$). The F-ratio for the three-way interaction was not significant ($F_{9,171} = 0.87$).

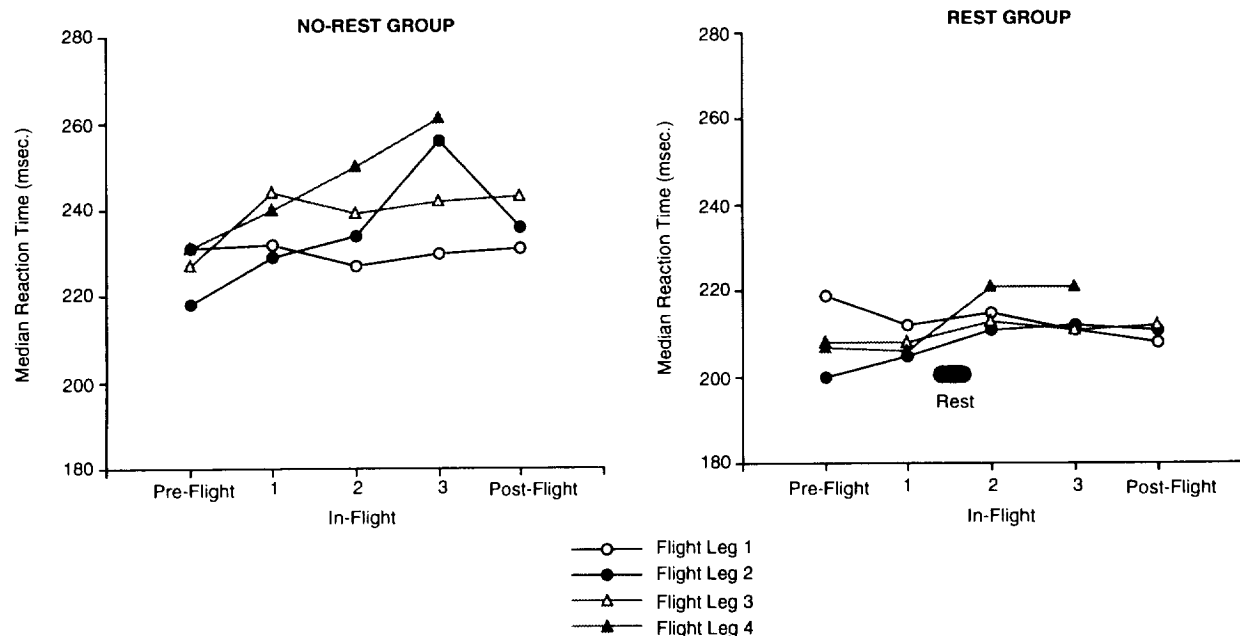


Figure 8. Median RT for each 10 min. PVT trial for RG and NRG across each flight leg; data points are averages of the medians within each group, and increases indicate poorer performance.

Two-way ANOVAs further clarified these effects. There were no significant main effects or interactions on study flight leg 1—the two groups were performing comparably at this time. However, on study flight legs, 2, 3, and 4, the NRG exhibited significantly more response slowing than the RG (main effect for condition: leg 2 $F_{1,19} = 11.73, p < .003$; leg 3 $F_{1,19} = 12.65, p < .002$; leg 4 $F_{1,19} = 8.92, p < .008$). Figure 9 illustrates this effect using data from the first and last study flight legs (1 and 4, respectively). The NRG displays a steady increase in median RT across flight leg 4 relative to flight leg 1, with differences becoming statistically significant midway and late in flight. Such changes are not evident in the RG.

Figure 10 displays the difference at each trial time-point between the two groups for data averaged across the four study flight legs. The preflight difference is not statistically significant, but on average the NRG was 10%-16% slower than the RG during the in-flight trials and during the postflight trial. The maximum difference occurs for in-flight trial 3 prior to TOD.

4.4.2 PVT Lapse Frequency

The most widely known effect of sleep loss on performance is lapsing, which refers to a period of response delay (block or gap), resulting in progressive unevenness (increased variability) in the performance of a fatigued subject. (For a complete discussion of this phenomenon and the lapse hypothesis, see refs. 6, 58.) Lapses have been shown to be associated with microsleep events in the EEG (refs. 6, 64-67). In the last two decades, there have been many studies showing that sleep-based fatigue results in lapsing and increased performance variability on short-duration RT tasks involving sustained attention (refs. 13, 47, 48, 51-55). Although a number of definitions have been used, lapses have most often been defined as RTs twice as long as the baseline RT

average (ref. 68). For a simple visual PVT of the kind used in this study, this value is 500 msec. (2 x 250 msec.). Thus, a lapse was defined as any RT longer than a half a second.

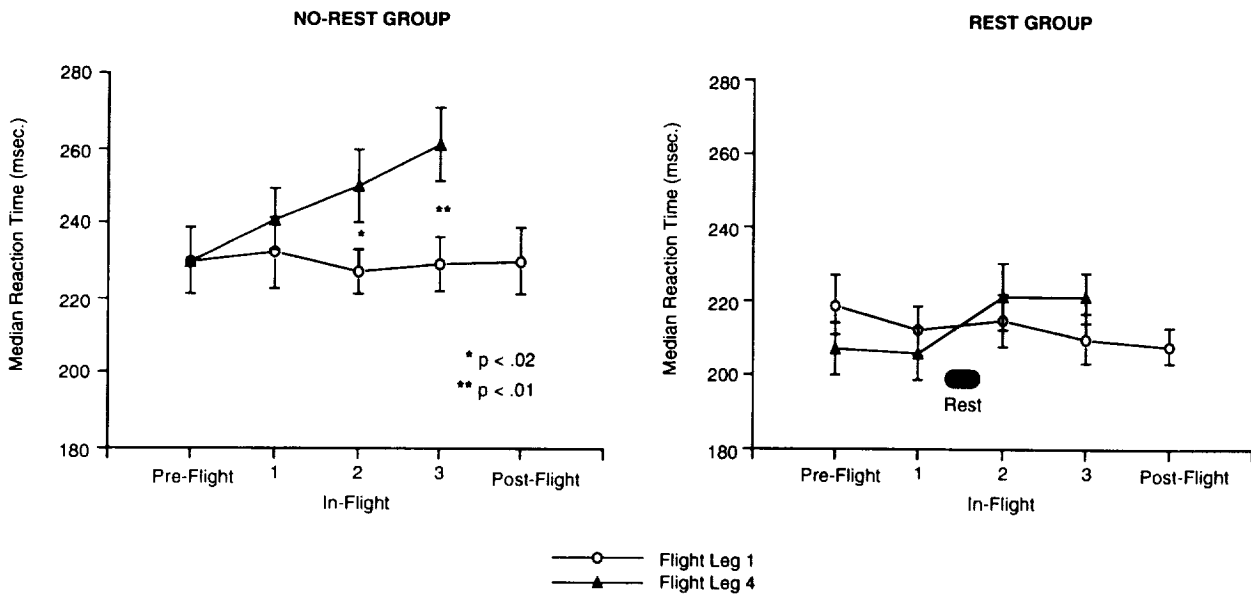


Figure 9. Median RT for each 10 min. PVT trial for both RG and NRG for day-flight leg 1 and night-flight legs 4; data points are averages (standard error bars) of the medians within each group. Increases indicate poorer performance; asterisks indicate significant differences with group by paired *t*-tests at specific time points.

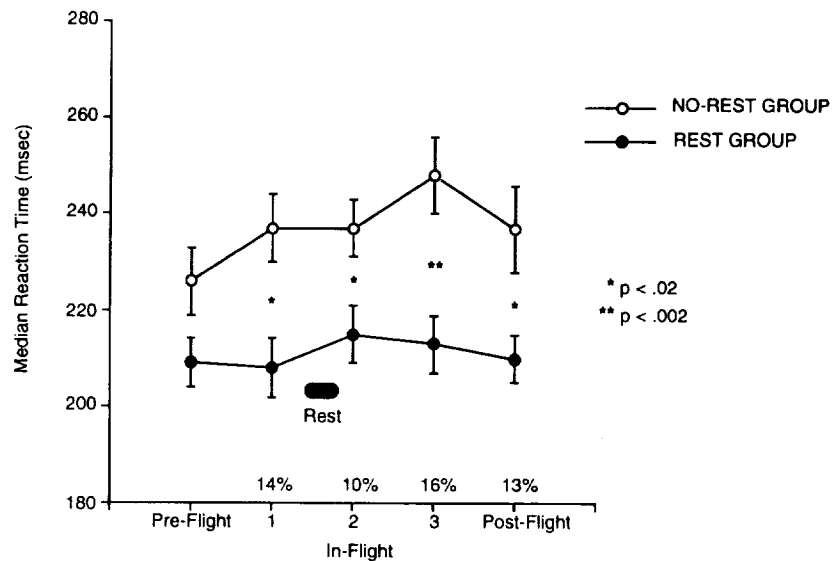
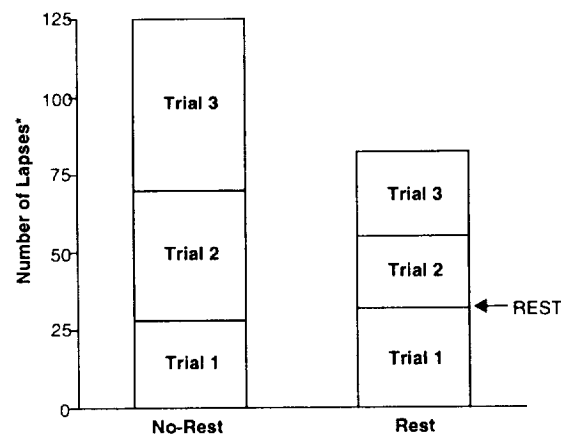


Figure 10. Median RT for each 10 min. PVT trial for both RG and NRG collapsed across all four flight legs; data points are averages (S.E. bars) of the medians within each group. Percentages indicate differences between group means at PVT trial times. Increases indicate poorer performance; asterisks indicate significant differences between groups by independent *t*-tests at specific time points.

There were a total of 283 lapses recorded for all 21 crewmembers in the study, representing about 1% of all PVT responses. As expected, lapses rarely occurred on PVT trials early in the study, when crews had fewer circadian disruptions and had accumulated less sleep debt. For all 21 crewmembers combined, the total number of lapses for the three in-flight PVT trials on day-flight leg 1 (HNL-OSA) was 20, which is only 7% of all lapses, and 10% of all in-flight lapses observed in the study. Lapses increased in frequency as crews progressed through the study, but the effect was more pronounced in the NRG (58% of all lapses) and on night-flight legs for both groups (60% of all lapses). Figure 11 shows the total number of lapses that occurred during PVT trials completed in the cruise portion of all four flight legs combined. The NRG had more total lapses in flight (N = 124) than the RG (N = 81), even though there were three more crewmembers in the RG than in the NRG. Moreover, the increase in lapses in the NRG is especially evident during in-flight performance trials 2 and 3, suggesting that the RG nap after trial 1 reduced the likelihood of increased lapsing later in the flight.

There were, however, broad individual differences in lapse frequency within each group. Five of nine NRG crewmembers had 10 or more in-flight lapses. Two of these crewmembers (an FO and a captain on different flights) had a disproportionately high total number of in-flight lapses (45 and 33, respectively), which together accounted for 38% of all in-flight lapses in the NRG. In contrast, only three of the 12 RG crewmembers totaled 10 or more lapses in-flight, and none had more than 14 lapses. Remarkably, five RG crewmembers (three captains and two SOs), as well as three NRG crewmembers (2 FOs and 1 SO), accumulated no more than four in-flight lapses on the PVT during the entire study, which is a rate of less than or equal to one lapse per flight.

Lapses, as more serious performance failures, require some consideration before statistical analysis because they comprise only a very small portion of all PVT responses and because there were such large differences in lapse frequency between individual crewmembers. Therefore, before conducting the ANOVAs, a square root transformation was used on the frequency count of the number of lapses to remove the proportionality between the mean and the variance (ref. 69). The results are presented in Figures 12-14. This analysis refers only to the number of lapses, without regard for their duration.



*Lapse defined as reaction time > 0.5 sec

Figure 11. Cumulative number of raw lapses (RTs > 500 msec.) for PVT trials completed during the cruise portion of all four flight legs for the RG and NRG. The cockpit nap (rest) occurred between in-flight PVT trials 2 and 3. Increases indicate poorer performance.

Figure 12 displays the average number of transformed lapses for the NRG and RG for each trial of each study flight leg. The NRG averaged increasing numbers of lapses across flight legs and trials relative to the RG, particularly during the third in-flight performance trial (near TOD) on study night-flight legs (2 and 4). There was, however, considerable difference between the two groups in variability, not fully obviated by the transformation. This was reflected in the three-way ANOVA. There were significant main effects for flight leg ($F_{3,57} = 4.81, p < .005$) and trial ($F_{3,57} = 4.14, p < .01$), but not for condition. There was no interaction for condition by flight leg, and only a trend for a condition by trial interaction ($F_{3,57} = 2.18, p < .10$). The flight leg by trial interaction was significant ($F_{9,171} = 2.77, p < .005$). The three-way interaction was not.

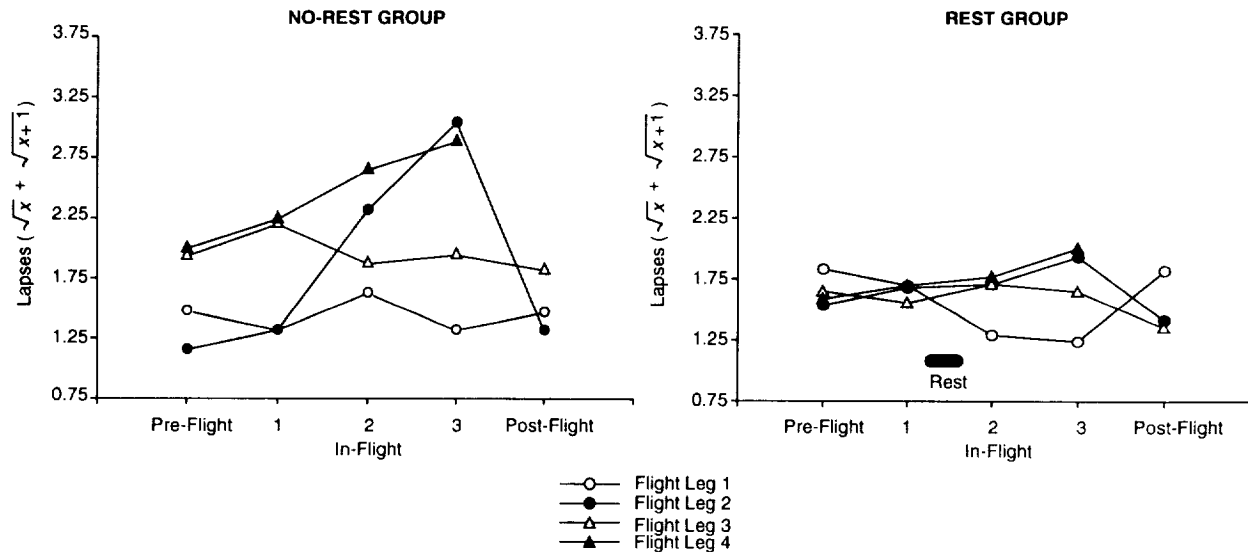


Figure 12. Mean number of transformed lapses ($RT > 500$ msec.) for each 10 min. PVT trial for both RG and NRG across each flight leg. Increases indicate poorer performance.

Two-way ANOVAs performed for data within each flight leg revealed that there were no main effects or interactions for day-flight legs (1 and 3) and for night-flight leg 4 (recall that this final leg did not have a postflight trial, reducing the degrees of freedom available). Night-flight leg 2 was associated with a significant condition by trial interaction ($F_{4,76} = 2.54, p < .05$). The NRG averaged increasing numbers of lapses during the flight relative to the RG. However, as noted above, not everyone in the NRG displayed increased lapsing on night flights, which accounts for the far greater variance around this group's mean on night-flight leg 4 (see fig. 19). As shown in figure 13, both groups had more lapses at TOD on night-flight leg 4 than at TOD on night-flight leg 1, but the increase from flight leg 1 to 4 is twice as large in the NRG as it is in the RG.

Figure 14 displays the difference at each trial time-point between the two groups for lapse frequency data averaged across the four study flight legs. At preflight and early in-flight (still pre-rest period), there were no differences between the RG and NRG in the average number of lapses or in the intersubject variability of lapsing. After the rest period, however, there were 30% more lapses during the two in-flight performance trials, and, more important, there was significantly greater variability ($p < .002$) at each time-point among NRG crewmembers (i.e., the intragroup variability of the NRG exceeded the intergroup variability). Thus, there was no sharp rise in lapses later in the flight for the RG. However, in the NRG, some subjects showed no increase in lapsing, whereas others had dramatic increases. It can be concluded that one benefit of the nap was to prevent some RG crewmembers from lapsing, especially during night flights.

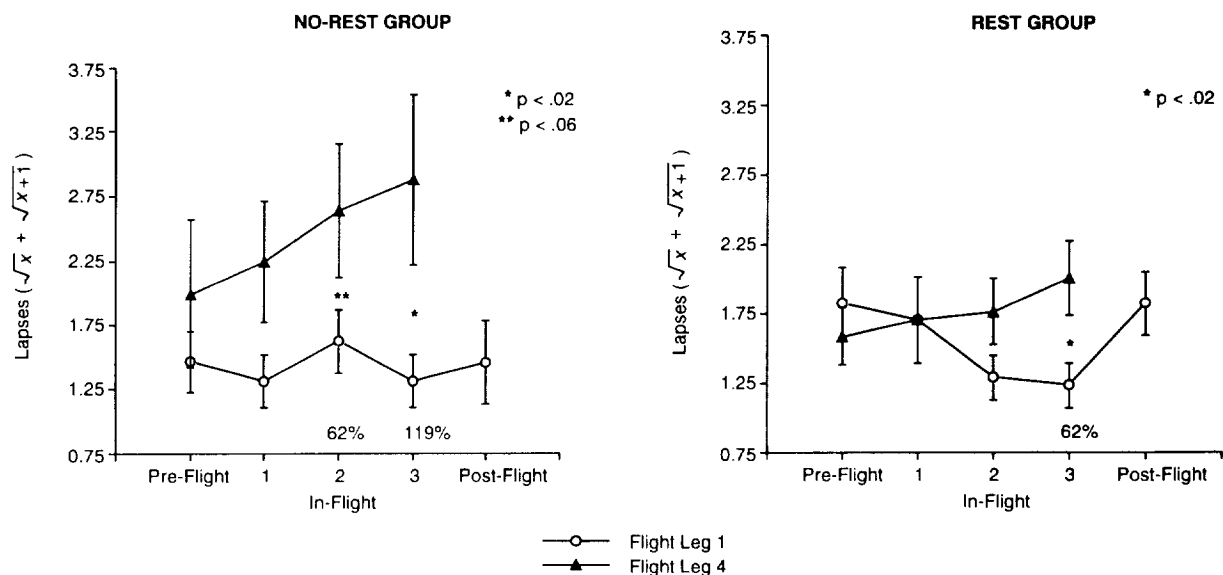


Figure 13. Mean (S.E.) number of transformed lapses ($RT > 500$ msec.) for each 10 min. PVT trial for both RG and NRG for day-flight leg 1 and night-flight leg 4. Increases indicate poorer performance. Percentages indicate differences between means of flight legs within each group at PVT trial times. Asterisks indicate significant differences with group by paired t-tests at specific time points.

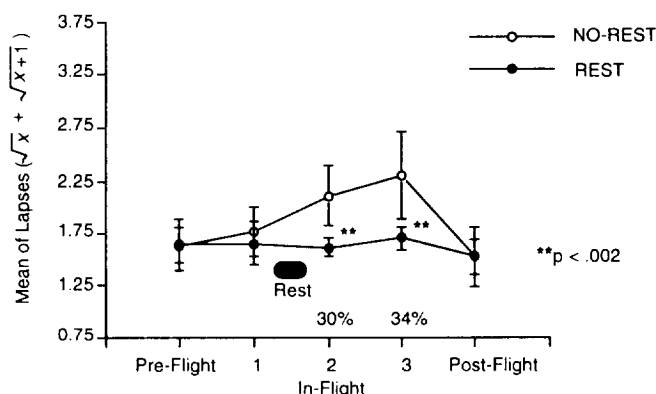


Figure 14. Mean (S.E.) number of transformed lapses ($RT > 500$ msec.) for each 10 min. PVT trial for both RG and NRG collapsed across all four flight legs. Increases indicate poorer performance. Percentages indicate differences between groups' means at PVT trial times. The asterisks indicate differences between groups in variance at in-flight trials 2 and 3. Asterisks indicate significant differences with group by paired t-tests at specific time points.

4.4.3 PVT Vigilance Decrement

The rate at which a response declines as a function of being repeated, or of time-on-task, reflects vigilance decrement. This same concept has been used in various literatures to define fatigue and habituation. There is a rich tradition of experimentally assessing changes in performance with time-on-task, and much of the classic literature on sleep deprivation effects used this approach (for reviews see refs. 6, 58). There is strong experimental evidence that sleep-based

fatigue results in accelerated decrements in responding across the 10 min. PVT (ref. 50). This observation has proved to be theoretically valuable in understanding the role of environment in fatigue-based deficits (ref. 19). In fact, Dinges has suggested that his time-on-task PVT performance metric, which is the vigilance decrement function, is best conceptualized as an index of “fatigueability.” This approach (ref. 50) has also provided a common metric by which to compare the magnitude of fatigue-based performance impairments between laboratory and field research, as seen in figure 15.

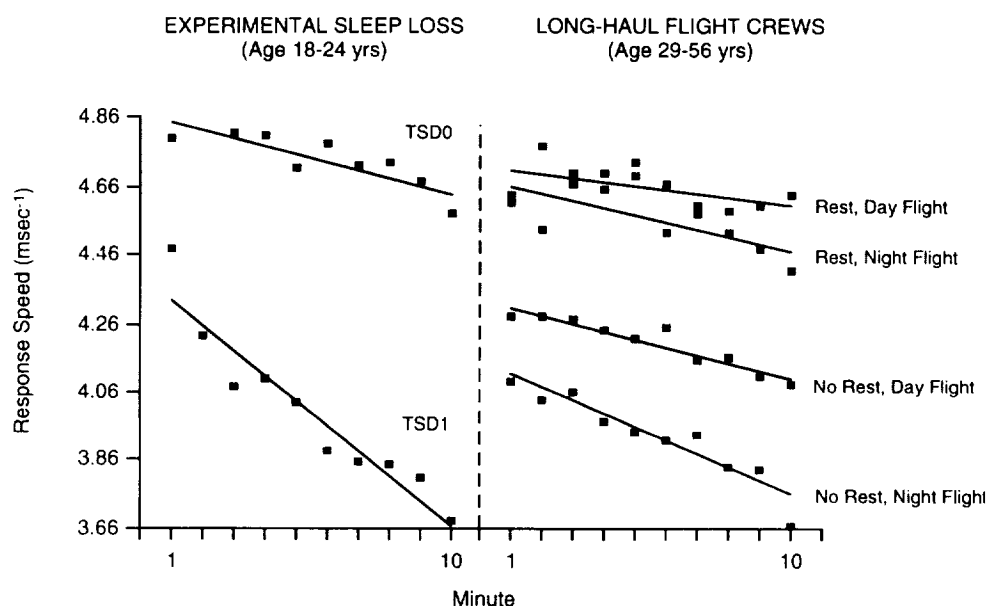


Figure 15. Vigilance decrements during PVT performance trial. Linear regression lines fitted by the method of least squares to the min.-by-min. average response speed across the 10 min. PVT. Data in right hand panel are from in-flight performance trials for RG and NRG during day-flight legs (mean of legs 1 and 3) and night-flight legs (mean of legs 2 and 4). For crews in the current study, only RTs from the second (mid-flight) and third (near TOD) in-flight PVT trials were used for each of the four lines. Data in left-hand panel are for comparison purposes from a study of nine healthy young adults performing the PVT during a day following a normal night of sleep (TSD0) and following 1 night without sleep (TSD1). Each regression line was fitted to the average performance across 10 min. Decreases indicate poorer performance.

The right half of figure 15 shows the linear regression lines fitted to the minute-by-minute average response speed across the 10 min. PVT for the RG and NRG on day-flight legs (mean of legs 1 and 3) and night-flight legs (mean of legs 2 and 4). (Note: Because of a $1/RT$ statistical transformation, a downward deflection indicates poorer performance.) Only RTs from second (mid-flight) and third (near TOD) in-flight PVT trials were used for each of the four lines, and data were averaged within subjects and then between subjects for comparable time-points to generate these functions (hence each regression line in fig. 15 represents the function fitted to the minute-by-minute averages, not the average of the functions for each crewmember). Linear regression lines were fitted to the transformed data by the method of least squares.

On the left-hand side of figure 15 are data from college students performing the PVT during a day following a normal night of sleep (TSD0 = total sleep deprivation 0, i.e., 3-17 hr. awake), and following 1 night without sleep (TSD1 = total sleep deprivation 1 night; i.e., 18-42 hr. awake). The mean vertical difference between lines (or their y-intercepts) reflects the overall response slowing engendered by fatigue from sleep loss and night flights. The slopes of the regression

equations provide an estimate of the fatigueability of crewmembers. In all cases in figure 15, the correlations of fit are statistically significant ($p < .05$ or higher), and range between .67 (rest night flight) and .95 (no-rest day flight).

As evidenced in earlier figures, the RG subjects had a higher mean response speed than the NRG subjects, and despite a considerable difference in age, their in-flight mean performance level (y-intercept) and fatigueability (slope) was near to that of healthy young adults who had not been sleep deprived. There is a tendency, evident in figure 15, for the RG subjects to be slightly slower and more fatigueable on night flights than on day flights. The difference is trivial, however, compared with how much better their average performance was relative to the NRG subjects, and compared to the average difference between day and night flights within the NRG. The NRG fatigueability function fitted to average data (slope = $-.039$) is less steep than that of the average laboratory subjects deprived of a night's sleep (TSD1 slope = $-.073$). However, the combined lower y-intercept and steeper slope suggest that during night flight, the NRG crewmembers were approaching a fatigue level that could be characterized as undesirable.

The fatigueability functions in figure 15 are based on regressions fitted to average data. Therefore, they do not indicate intersubject variability, or whether the greater slope for the NRG on night flights is statistically different from their day flights. Also, they do not determine how these differences compare with the day and night slopes for the RG. To obtain these answers, regression lines were fitted to the transformed minute-by-minute data for each individual crewmember. Those crewmembers in either group who had a y-intercept difference between day flight and night flight of more than 0.2 (which is between 8 and 18 msec. in raw RT) were excluded from the analyses. The reason for this criterion was to assess differences in fatigueability (slope), given roughly comparable initial levels of functioning (y-intercept). Application of this criterion reduced the NRG from nine to seven subjects, and the RG from 12 to 8 subjects. Despite the loss of degrees of freedom, this approach yielded an important observation.

Although there continued to be significant mean differences in y-intercepts between the NRG and RG, there were no significant differences within either subgroup in y-intercepts for day and night flights (which was the purpose of applying the criterion). The average (SD) regression slope for the eight RG crewmembers during day flight was $-.026$ (.025); during night flight it was $-.023$ (.023). The average regression slope for the seven NRG crewmembers during day flight was $-.022$ (.012); during night flight it was $-.047$ (.018). A two-way repeated-measures ANOVA yielded a significant interaction ($F_{1,13} = 6.94$, $p < .021$), but no main effects. The night-flight slope for the NRG was significantly steeper than its day-flight slope ($t = 4.29$, $p < .002$), and steeper than the RG night slope ($t = 2.18$, $p < .048$).

Thus, given comparable initial levels of performance, only the NRG crewmembers displayed greater fatigueability on night flights than on day flights. This suggests that one outcome of the cockpit nap was to prevent increased fatigueability on the night flight. The magnitude of the difference is remarkable. During night flight, the average NRG response speed declined with time-on-task (mean slope = $-.047$) twice as fast as that of the RG (mean slope = $-.023$). This result is more noteworthy when one considers that the two NRG crewmembers excluded from the analyses because of large differences in their day and night y-intercepts, also had the poorest overall level of functioning (lowest y-intercepts) during night flight of all 21 crewmembers studied. Thus, the RG crewmembers who were permitted to take the in-flight nap during night flights were significantly less fatigueable than the NRG not permitted to sleep.

4.5 Physiological Alertness/Sleepiness: Microevent Analysis during Critical Operational Phase

An intensive analysis of specific EEG frequency and EOG changes associated with reduced physiological alertness was conducted on the period from 1 hr. before TOD through landing. This critical phase of operation, including descent and landing, averaged about 90 min. and was analyzed for both the rest and no-rest groups. The entire 90 min. period was scored for the individual occurrence of three specific physiological events: (1) EEG alpha activity (8-12 Hz); (2) EEG theta activity (3-7 Hz); and (3) EOG slow-rolling eye movements (SEMs; > 100 uV amplitude, > 1 -sec).

duration). The duration of each microevent occurrence was scored according to three time bins: (1) 5-10 sec., (2) 11-15 sec., and (3) >15 sec.

The physiological microevent data were examined in two ways, and the results of these analyses are presented. First, the raw microevent data were used for an overall descriptive analysis. Second, statistical analyses were conducted in a manner that paralleled the statistical analysis of the PVT lapse data. The specific statistical approach and results are presented.

4.5.1 Raw Data: Descriptive Analysis

The nine subjects in the NRG, each flying four legs, provided a total of thirty-six 90 min. periods. Six of these 90 min. periods were lost because of equipment malfunctions and, therefore, thirty (83%) were available for analysis of microevents in the NRG. The twelve subjects in the RG, each flying four legs, provided a total of forty-eight 90 min. periods. Four of these 90 min. periods were lost because of equipment malfunctions, and the remaining forty-four (92%) were available for analysis of physiological microevents.

The following descriptive analysis of the raw data utilized cumulative totals of the microevent occurrences (a composite score of total alpha, theta, and SEMs microevents). The cumulative total microevents that occurred for all twenty-one crewmembers was 154. The nine NRG crewmembers had a total of 120 microevents (78%), whereas the twelve RG crewmembers had a total of 34 microevents (22%). As expected, most of these microevents, 132 (86%), occurred in the hour before TOD. In the NRG, 98 microevents occurred before TOD, with 22 microevents in the period from TOD through landing. In the RG, all of the 34 microevents occurred before TOD.

There were broad individual differences in the occurrence of physiological microevents. Seven of nine (78%) NRG crewmembers had at least one microevent. Four of these seven (two captains and two FOs) had 9 or more total microevents that together accounted for 84% of the total NRG microevents. Two of these four crewmembers (one captain, one SO on the same trip) accounted for 52% of the total NRG microevents. Six of the twelve (50%) RG crewmembers had at least one microevent occurrence. Two of these six (both SOs) had 9 or more microevents and accounted for 59% of the total RG microevents.

Overall, there were four NRG crewmembers who had more than 11 microevents; an NRG captain had the most occurrences, 42. At the other end of the range, only two NRG crewmembers had as few as 6 microevents. The highest number of microevent occurrences for a crewmember in the RG was 11. Another RG crewmember had 9 microevents and the remaining four RG crewmembers had less than 6 events.

The cumulative total microevents were composed of 87 alpha occurrences (56%), 52 SEM occurrences (34%), and 15 theta occurrences (10%). Most of the microevents were of short duration, 83 (54%) lasting 5-10 sec. Sixty-two (52%) of the NRG microevents were in this time bin, whereas 21 (62%) of the RG microevents fell in this range. Only 23 (15%) of the total microevent occurrences lasted over 15 sec.

The distribution of cumulative total microevents across study flight legs is presented in table 27. It shows that 49% occurred on study leg 4 (a night flight). The NRG had 40% of their microevents on the last study-leg, and the RG had 82% of their occurrences. On study leg 1, there were 21 microevents (18% of NRG) in the NRG and only 1 RG occurrence. Also, most of the microevents, 106 (69%), occurred on night flights (study legs 2 and 4), the NRG having 77 microevents (64%) during the nights and the RG having 29 (85%). However, even here there was tremendous individual variation. The crewmember (NRG) with the most microevents had 37 of his 42 occurrences (88%) during day flights. The crewmember (also NRG) with the next highest total number of microevents had 26 of his 28 (93%) occurrences on the last study flight leg at night. In the RG, the two crewmembers with the highest number of microevents had all of their occurrences on the last study flight leg at night.

Table 27. Raw data-descriptive analysis: cumulative total microevents across study-flight legs

Study flt. leg	RG	NRG	Cumulative totals
1	1	21	22
2	1	29	30
3	4	22	26
4	28	48	76
Cumulative totals	34	120	154

In figure 16, the total cumulative microevents for the NRG (left figure) and RG (right figure) are portrayed in 10 min. time bins across the last 90 min. of flight. As previously indicated, this shows the occurrence of 22 NRG microevents during the last 30 min. of flight (descent and landing phase); all of the RG microevents occurred before TOD.

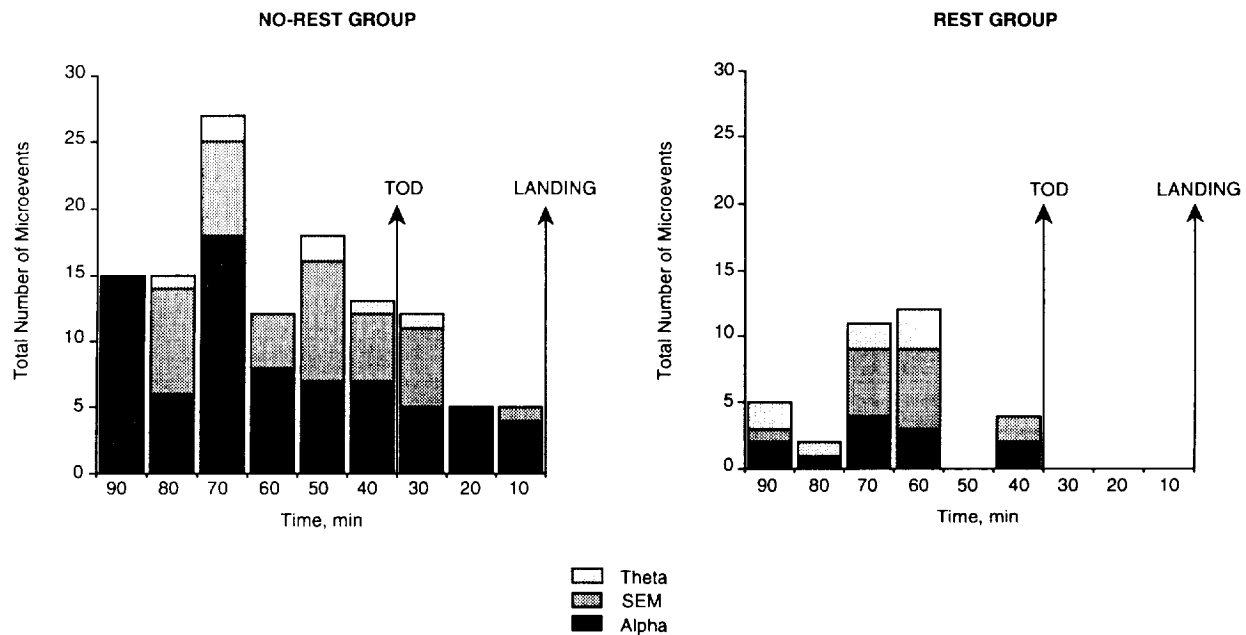


Figure 16. Total cumulative microevents for the NRG and RG portrayed in 10 min. time bins over the last 90 min. of the flight (from about 1 hr. before TOD, through TOD and landing).

4.5.2 Statistical Analysis of Microevent Occurrences

The statistical analysis of the microevents paralleled the approach used to examine the statistical significance of the lapse results from the PVT. As previously stated, the lapses required some consideration before statistical analysis, because there were such large individual differences in lapse frequency among crewmembers. A square root transformation was used on the frequency count of the number of lapses to remove the proportionality between the mean and the variance (ref. 69). This same consideration applies to the statistical analysis of the microevents associated with physiological sleepiness. The occurrence of physiological microevents was quite variable

among crewmembers—some individuals had no microevent occurrences, whereas others had many. Therefore, paralleling the analysis of the lapse data, a square-root transformation (square root of x plus the square root of $x + 1$) was performed to increase the homogeneity of the variance (ref. 69). The purpose of the square root transformation was to reduce the variability of the data set by normalizing the distribution. This normalization reduces the potentially biased representation of specific individuals who had a high number of microevent occurrences.

The ANOVA was then conducted on the transformed data set. Levene's test for equality of variance was examined to determine whether the transformation had normalized the distribution of the data. A significant finding on the Levene's test indicated that a significant difference between the variances remained and that the transformation had not fully normalized the distribution. In this situation, the appropriate nonparametric statistical test was conducted on the raw data (either a Mann-Whitney U rank-sum test for comparison of two factors or the Kruskal-Wallis one-way ANOVA for comparison of more than two factors). The averages (and standard deviations) for the transformed data and the significant findings are presented. Statistical analyses were conducted using the total microevent occurrences (a composite score of total alpha, theta, and SEMs) and also the three separate microevent categories (i.e., alpha, theta, and SEMs).

Overall, the NRG crewmembers averaged significantly more cumulative total microevents, 6.37 (SD = 4.04), than the RG crewmembers, whose average was 2.90 (SD = 2.19) ($F_{1,19} = 6.44$, $p = .02$) (fig. 17). Analysis of alpha, theta, and SEM totals demonstrated a significant difference in the average SEM occurrences between groups. The NRG averaged 3.72 (SD = 2.31) SEM occurrences, and the RG averaged 1.95 (SD = 1.55) ($F_{1,19} = 4.45$, $p = .048$) (fig. 17). A composite total of alpha and theta microevents, without SEM occurrences, also demonstrated significantly more microevents in the NRG than in the RG ($F_{1,19} = 6.38$, $p = .02$).

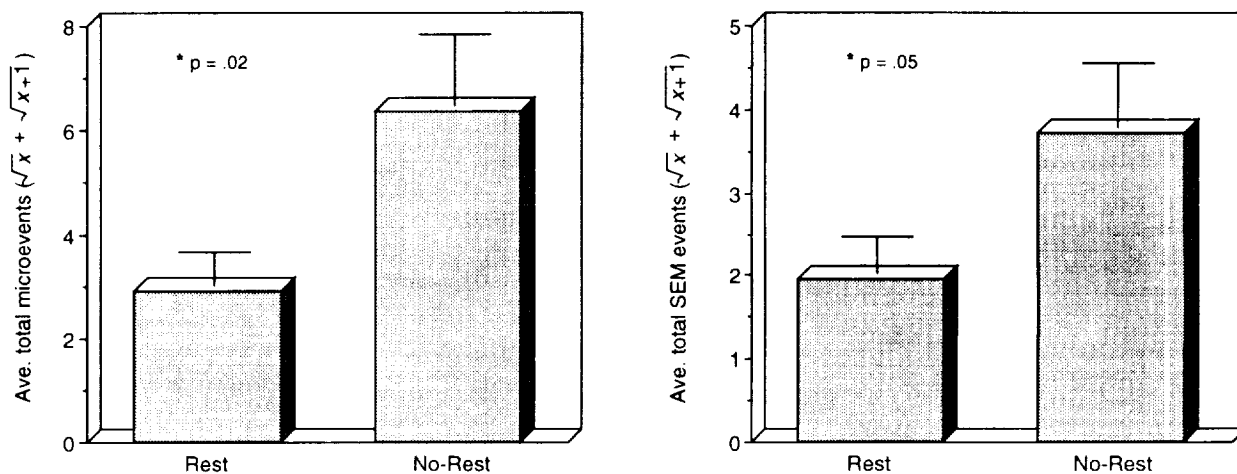


Figure 17. Average number of total microevents occurrences (left figure) and SEM occurrences (right figure) by each crewmember in RG and NRG. Transformed (square root) data are represented in each figure.

There was a significant finding regarding the duration of total microevents, with the most events occurring in the shortest time bin. The average number of total microevents for each of the time bins was 5-10 sec. = 3.43 (SD = 2.42), 11-15 sec. = 2.63 (SD = 1.98), and >15 sec. = 1.35 (0.64) ($F_{1,19} = 4.55$, $p = .015$) (fig. 18). There also was a significant finding for the duration of SEMs, with most events lasting between 5 and 10 sec. The average number of SEMs for each of the time bins was 5-10 seconds = 2.29 (SD = 1.55), 11-15 sec. = 1.70 (SD = 0.99), and >15 sec. = 1.28 (0.90) (Kruskal-Wallis = 7.14, $p = .028$) (fig. 18). A composite total of alpha and theta microevents, without SEM occurrences, also demonstrated the same significant time bin effect ($F_{1,19} = 6.31$, $p = .01$).

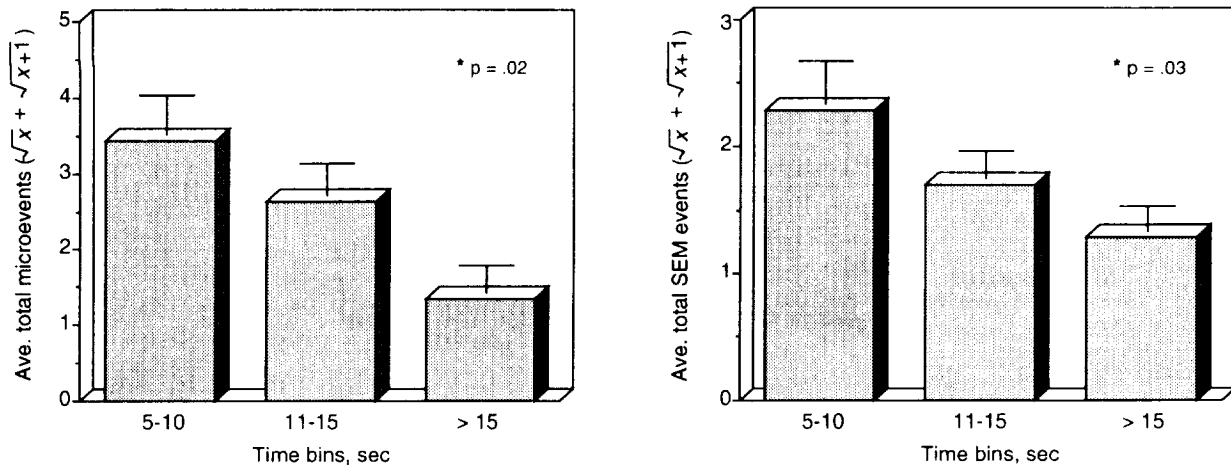


Figure 18. Average number of total microevent occurrences and SEMs for each crewmember of the study group separated by time bins. Transformed (square root) data are represented in each figure.

The period before TOD covered about 60 min., and the period from TOD through descent and landing was about 30 min. Therefore, as expected, the average number of total microevents for the period before TOD, 4.14 (SD = 3.18), was significantly greater than the average number of total microevents from TOD through descent and landing, 1.71 (SD = 1.61) (Mann-Whitney U = 323.5, $p = .004$) (fig. 19). Also, there were significantly more alpha and SEMs occurrences before TOD. The average number of alpha occurrences before TOD was 2.89 (SD = 2.71); the average from TOD through descent and landing was 1.49 (SD = 1.29) (Mann-Whitney U = 293, $p = .026$) (fig. 19). The average number of SEM occurrences before TOD was 2.52 (SD = 2.00); the average from TOD through descent and landing was 1.29 (SD = 0.80) (Mann-Whitney U = 292, $p = .024$) (fig. 19).

Significantly more SEMs occurred on the last study-flight leg. The average number of SEMs by study leg were as follows: leg 1 = 1.07 (SD = 0.31), leg 2 = 1.70 (SD = 1.22), leg 3 = 1.21 (SD = 0.98), and leg 4 = 2.02 (SD = 1.64) (Kruskal-Wallis = 9.76, $p = .02$) (fig. 20).

Two significant findings emerged for microevent occurrences on day versus night flights. The average number of total microevents on each night flight, 2.52 (SD = 1.72), was significantly greater than the average on each day flight, 1.65 (SD = 1.71) (Mann-Whitney U = 694, $p = .035$) (fig. 21). Also, the average number of SEM occurrences was significantly greater on night flights, 1.86 (SD = 1.09), than on day flights, 1.14 (SD = 0.51) (Mann-Whitney U = 652, $p = .002$) (fig. 21). A composite total of alpha and theta microevents, without SEM occurrences, also demonstrated significantly more microevents on the night flights than on the day flights (Mann-Whitney U = 676, $p = .02$).

4.5.3 Sleep Latency Results

As indicated earlier, the speed of falling asleep (sleep latency) is an accepted laboratory measure of physiological sleepiness, increased sleepiness being associated with shorter sleep latencies (i.e., falling asleep quickly). The laboratory standard for a level of excessive physiological sleepiness is a sleep latency of 5 min. or less, sometimes referred to as the “twilight zone” (refs. 21, 27). In this study, the RG average was 5.6 min. to fall asleep. (For the RG (24) subjects this average was 4.1 min.) This indicates that overall, this group of volunteers fell asleep quickly and close to the laboratory range that indicates excessive physiological sleepiness.

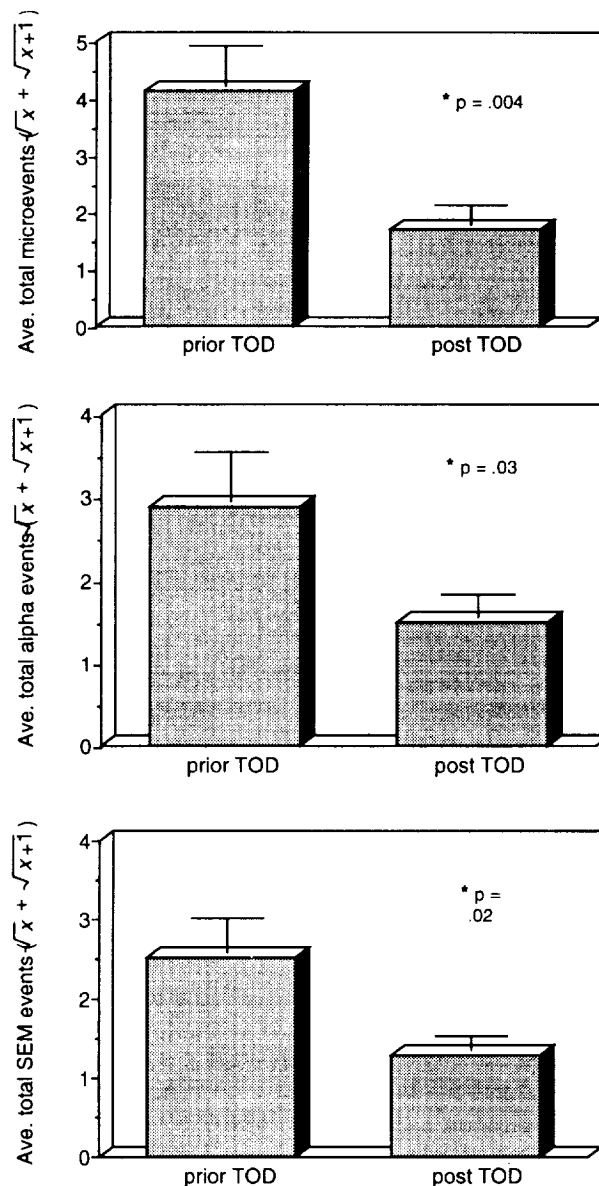


Figure 19. Average number of total microevent occurrences, alpha, and SEM for each crewmember of the study group separated by prior-to TOD and following (TOD) for each study leg. Transformed (square root) data are represented in each figure.

4.5.4 Subjective Alertness Ratings

Crews rated their alertness every hour throughout each flight leg. Following each flight they retrospectively rated their overall alertness during the flight. Both types of subjective ratings were collected on 10-cm analogue scales rated from most drowsy to most alert. Because of missing data, in-flight alertness ratings were subdivided into the average of two ratings immediately before and after the rest/control period. Thus, the three-way ANOVA on self-reports of in-flight subjective alertness was structured to include both conditions (rest vs. no-rest), four flight legs, and two phases within each flight leg (pre-control vs. post-control).

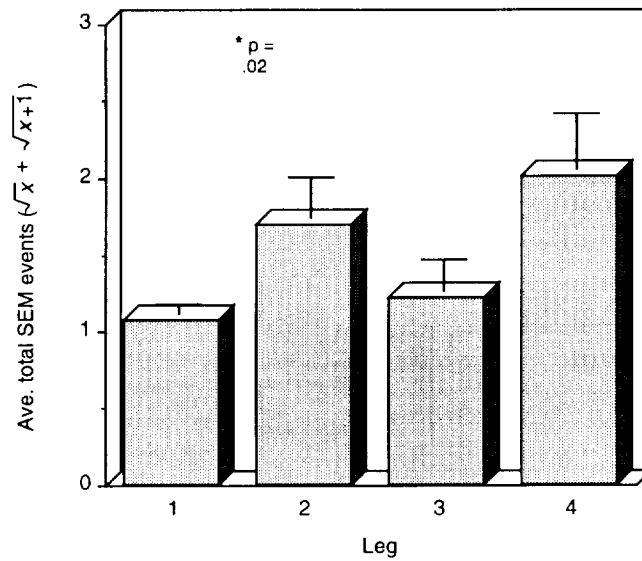


Figure 20. Average number of total occurrences of SEM for each crewmember of the study group over each study leg. Transformed (square root) data are represented.

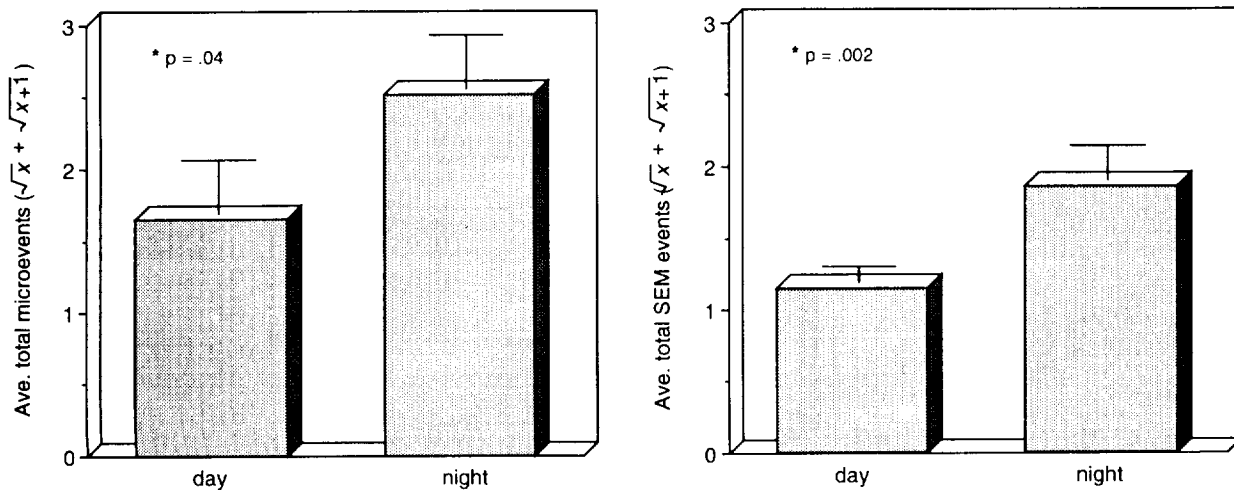


Figure 21. Average number of total microevent occurrences and SEMs for each crewmember of the study group per day and night-flight legs. Transformed (square root) data are represented in each figure.

The analysis of alertness ratings yielded a main effect for flight leg ($F_{3,48} = 19.2$, $p < .0005$). Not surprisingly, subjective alertness was lower on night flights (legs 2 and 4) than on day flights (legs 1 and 3). There was also a main effect for phase of flight ($F_{1,16} = 28.8$, $p < .0005$), resulting from post-rest alertness ratings being lower than pre-rest ratings. However, this varied with flight leg, yielding a significant leg-by-phase interaction ($F_{3,48} = 12.8$, $p < .0005$); subjective alertness decreased from the pre-rest to the post-rest phases of flight for flight legs 2, 3, and 4, but not on flight leg 1 (fig. 22).

The nap did not appear to affect subjective alertness ratings, although there was a trend for the RG to average higher alertness ratings overall than did the NRG (condition main effect, $F_{1,16} = 3.9$, $p = .063$). The nap did not interact with flight leg or phase of flight, but there was a significant interaction among condition, flight leg, and phase of flight ($F_{3,48} = 3.1$, $p = .033$). On flight leg 1,

the nap resulted in increased alertness ratings in the RG, whereas all other flight legs for both groups resulted in comparable decreases in subjective alertness across the rest/control period. Consequently, there was no systematic evidence that the nap altered the decrease in subjective alertness experienced as time passed on a flight leg. An analysis of postflight reports of alertness also showed no differential effects of the nap on alertness, although like their ratings of in-flight alertness, crews reported themselves significantly less alert on night-flight legs (2 and 4) than on day-flight legs (1 and 3) ($F_{3,33} = 5.8, p < .002$).

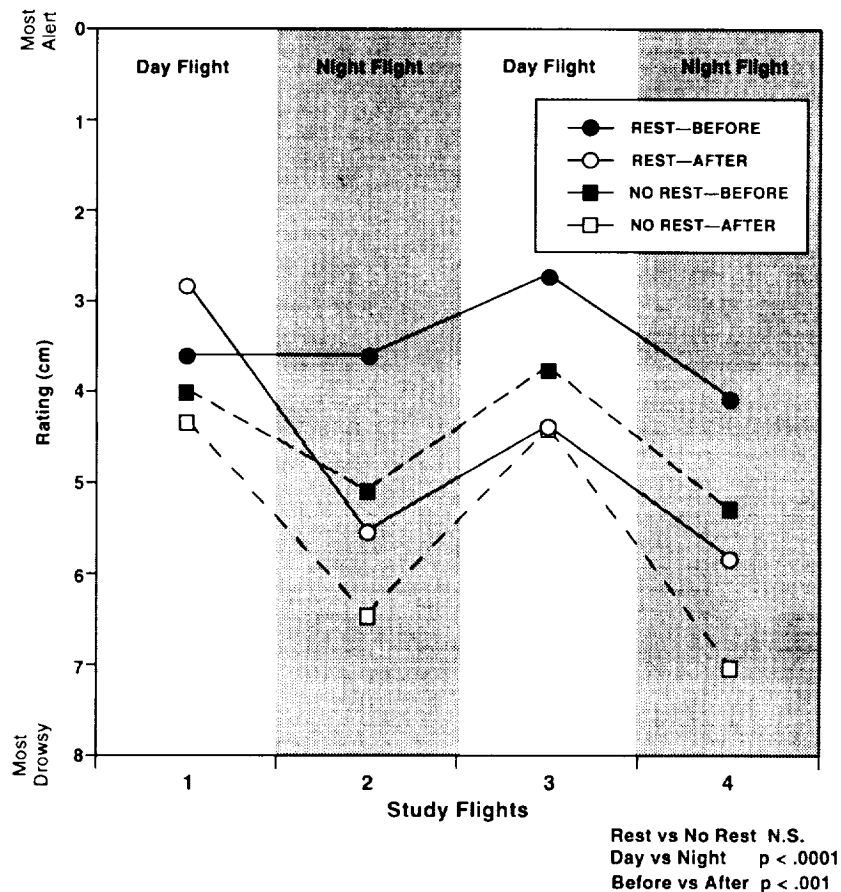


Figure 22. Mean subjective alertness ratings for subjects in RG and NRG conditions for each of the four flight legs.

Thus, in-flight naps were associated with improved performance and physiological measures of alertness. However, they were not associated with decreased subjective fatigue or improved subjective alertness. This failure to find naps affecting subjective activation may be due to the way in which data were averaged because of missing data, but the finding is also consistent with results from laboratory studies of naps taken during periods of sustained wakefulness (ref. 14). In those studies, naps clearly enhanced performance and physiological activation, but did not change subjective activation. Although the reasons for this finding in the current study are unclear, it is further evidence that subjective reports from flight crews do not always reflect accurately the level of physiological sleepiness that may be present (refs. 39, 40). As expected, crews did report decreased alertness on night flights, and lower alertness as time progressed within each flight, and these two effects were robust. However, against the backdrop of such temporal effects, in-flight naps did not result in subjective changes comparable to those recorded in the objective indices of alertness.

4.6 Layover Sleep: Results from Wrist Activity Monitor and Sleep Log

Each crewmember wore a wrist activity monitor (WAM) continuously for 1 to 5 days before the duty cycle, while on duty and throughout each layover, and for 1 to 3 days after the duty cycle. The actigraph provided objective documentation of crewmembers' self-reported sleep episode. Used in this way, the actigraph helped validate the sleep log and allowed "correction" of the self-reported layover sleep amounts. Thus, if a crewmember reported sleeping at a time when the actigraph was showing active motility identical to wake ambulation, then the sleep report was discounted. These rather frequent errors usually involved a crewmember apparently misrecording or misperceiving the time of a sleep episode (e.g., the actigraph indicated that a layover sleep began at 0645 GMT, but the crewmember logged it at 0845 GMT)—these kinds of errors are common in retrospective reports. Thus, the actigraph permitted an objective check on times when crewmembers reported sleeping, but it could not guarantee that sleep was actually present during a period of low motility (especially a short-duration period) and it could not provide data on the stage of sleep at any given time. For these latter goals, polysomnography is necessary.

Following detailed correction of the sleep log using actigraphic information, the timing of layover sleep and the cumulative sleep loss across duty cycle days were calculated for each crewmember. The analysis of the data focused on two questions, the first of which was concerned with the extent to which the cockpit naps alter the sleep debt and layover sleep patterns, and the second with individual differences in sleep debt.

4.6.1 Cumulative Sleep Loss and Cockpit Rest

Figure 23 displays actigraphic rest/activity patterns from a captain during two phases of the study. The top panel shows his motility during the 73 hr. period at home, immediately before beginning a duty cycle; the bottom panel shows his motility pattern for the second 73 hr. period of duty (during days 4, 5, and 6). The pattern and timing of sleep (black horizontal bars in the figure) changed during duty, but there is also a clear decrease of 6% (4.38 hr.) in the proportion of time occupied by sleep. The patterns for trip leg 2 (duty days 1, 2, and 3) and trip leg 4 (duty days 7, 8, and 9) are similar to the bottom panel of figure 23 and illustrate clearly that this NRG captain developed a cumulative sleep debt during the study.

The development of a cumulative sleep loss portrayed in figure 23 was displayed by most of the crewmembers in the study. Similar to the results of an earlier study examining long-haul crews flying polar routes (ref. 70), not all crewmembers developed a pattern of cumulative sleep loss during a duty cycle. Sasaki and his colleagues reported that 10 of 12 long-haul crewmembers (83%) suffered a cumulative sleep debt during operations, that is a debt of at least 4 hr. by the ninth day, with the worst case reaching 25 hr. of lost sleep by the ninth day. The results from the current study are very similar. Eighteen of a total of 21 crewmembers (86%) had a cumulative sleep debt of at least 4 hr. by the ninth day, with the worst case reaching 22 hr. When combined with the earlier study, it suggests that 85% (28/33) of long-haul crewmembers develop a cumulative sleep debt after repeated days of transmeridian duty.

Sasaki et al. (ref. 70) did report that two long-haul crewmembers (17%) actually gained at least 4 hr. of sleep by the ninth day of a duty cycle, but this occurred in only one (5%) crewmember in the present study. Two other crewmembers had neither a sleep debt nor a gain. Interestingly, the three crewmembers without a cumulative sleep debt in the study also reported relatively short periods of sleep daily while off duty at home. In fact, the crewmember who gained sleep by day 9 of the duty cycle (+8.5 hr.) reported the least sleep at home off duty (6.5 hr./day). The pattern for the other two crewmembers (no sleep debt) was similar: the first had +0.6 hr. cumulative gain by day 9, and reported 7.0 hr./day of sleep at home; the second had -1.0 hr. cumulative loss by day 9, and reported 7.3 hr./day of sleep at home. Nevertheless, the vast majority of crewmembers developed a sleep debt as the study progressed.

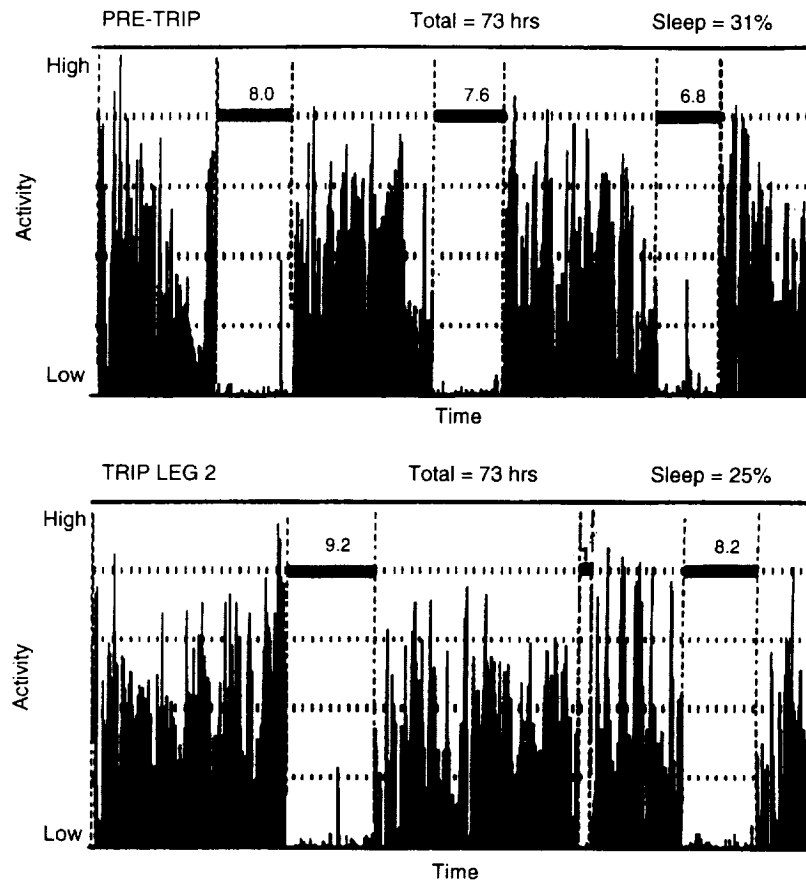


Figure 23. Wrist actigraphic recordings from a NRG captain during two phases of the study. Top panel shows rest/activity pattern during the 73 hr. period at home, immediately before beginning a duty cycle. Bottom panel shows rest/activity pattern for the second 73 hr. period of duty (during days 4, 5, and 6). Periods of sleep are represented by horizontal bars. The proportion of sleep time reflected in each record is shown the upper right-hand corner of each panel.

To determine whether the cockpit rest altered the cumulative sleep debt of crewmembers, analyses examined the cumulative sleep debt of the RG subjects both with and without the cockpit naps included, as well as sleep debt of the NRG subjects. Figure 24 displays the average sleep debt for these three conditions and the first-order linear regressions fitted to the data from each condition. There was no statistically significant difference between the NRG and the RG in cumulative sleep loss functions. In the RG, when the cockpit nap is not included, there was a trend toward a greater sleep debt. This appeared to be largely a result of the RG sleeping somewhat less than the NRG during the layovers in Honolulu and Los Angeles. There is no evidence that this was related to naps in-flight, for it did not occur at other layovers.

It is important to highlight that the cockpit nap did not have a significant effect on the cumulative sleep loss function of the RG. This suggests that whatever benefits the nap had for performance and alertness, those benefits were not created by a diminution of the cumulative sleep loss experienced by crews. By the ninth day of duty, with or without planned cockpit rest, crewmembers averaged approximately 1 full night of lost sleep. Rather than attenuating this more chronic source of fatigue in long-haul operations, it appears that the cockpit naps functioned as an acute relief for fatigue, promoting alertness but not affording enough sleep to circumvent accumulated loss over many days.

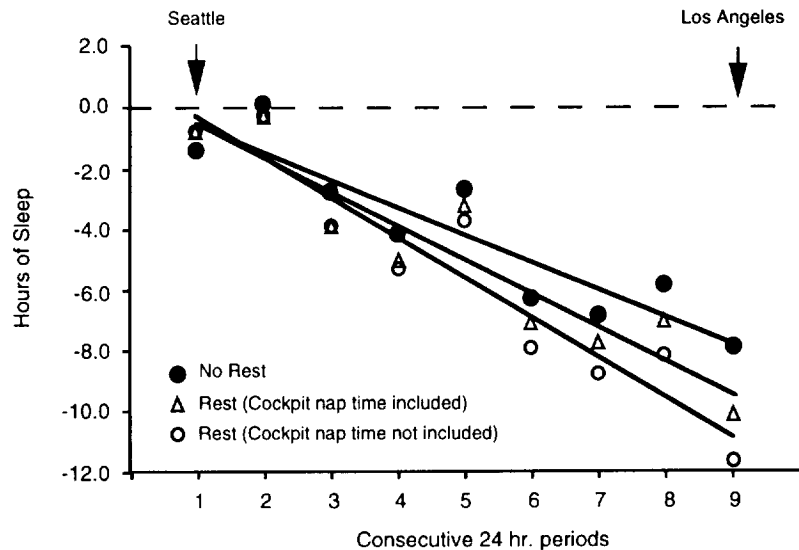


Figure 24. Mean hours of cumulative sleep loss (by combined actigraph and sleep log data) during nine consecutive 24 hr. periods of the study duty cycle (through the LAX layover). Data are shown for the NRG and RG with and without the cockpit rest periods included. Linear regression functions fitted to each group's data are also displayed.

4.6.2 Layover Sleep Episodes

Two findings, the accumulated sleep debt developed by most crewmembers and the lack of an associated effect from the cockpit naps, prompted an evaluation of the timing of layover sleep episodes. This was examined for the seven approximately 24 hr. layovers of the study duty cycle. The assumption commonly made is that a 24 hr. layover should provide adequate opportunity for rest and sleep. Yet as demonstrated above, the vast majority of crewmembers developed a sleep debt. Figure 25 displays the average percent of time spent asleep (by combined actigraph and sleep log) at each layover for both RG and NRG crewmembers combined. On four of the seven layovers, crews averaged about 40% sleep time, which is comparable to 9.6 of 24 hr. This is not an inconsequential amount of sleep, and it suggests that crews were endeavoring to obtain reasonable amounts of sleep on layovers.

Both RG and NRG crewmembers obtained about 5% less sleep at two layovers (Osaka and Narita2), for reasons that are not yet clear. Osaka was the longest duration layover (29.4 hr.—see table 1), which may have resulted in proportionately less sleep being obtained. Similarly, both groups obtained the highest proportion of sleep on the Los Angeles layover, spending an average of 45% (10.8 of 24 hr.) sleeping. There are three factors that may have contributed to this increase in layover sleep at LAX: (1) the Los Angeles layover was on home time for all but a few of the crewmembers; (2) it occurred near the end of the duty cycle, when a sleep debt had already developed for most crewmembers; and (3) it occurred immediately before the flight with the longest duty time (LAX to SEL). Consequently, when reaching Los Angeles, crews were tired, they were sleeping at times that were consistent with their home circadian cycle, and they were aware that the next trip leg would involve the longest duty duration of the trip.

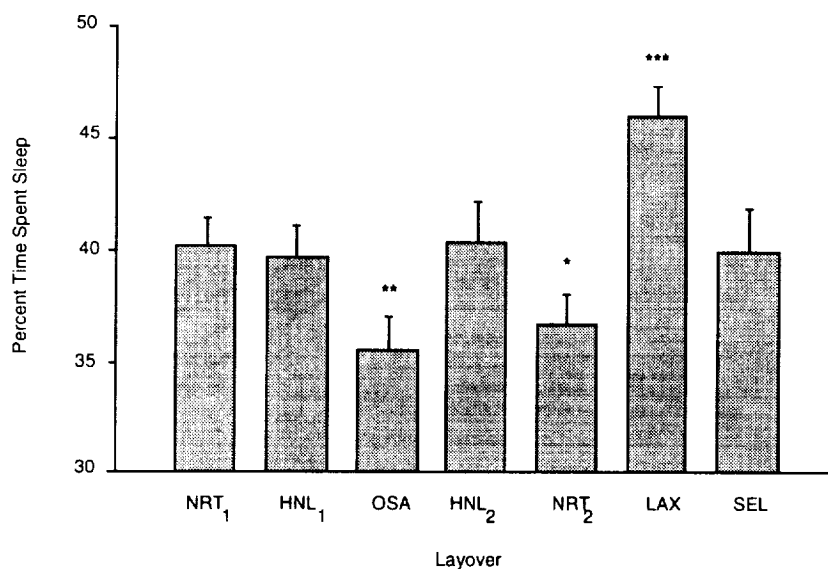


Figure 25. Mean (S.E.) proportion of time spent asleep (by combined actigraph and sleep log) at each of seven duty cycle layovers for all 21 crewmembers (RG and NRG). Asterisks highlight layovers with sleep percentages significantly below or above the 40% levels of NRT1 and HNL1 ($p < .05$, ** $p < .01$, *** $p < .001$).*

The relatively high proportion of sleep time on layovers appears inconsistent with the sleep debt that was accumulated by most crewmembers. However, the inconsistency disappears when the full duty work-rest cycle is considered. Figure 26 displays the average proportion of time spent asleep 1) when crews were off duty, at home; (2) when they were on layover; and (3) when layover was combined with subsequent duty time. The 24 hr. day at home can be subdivided into a work:rest ratio of 1:2. This represents the 8 hr. of the day that are typically devoted to work (even when not strictly working) and the remaining 16 hr. devoted to rest (to include exercise, eating, social activity, sleep). At home, crews spend about 33% of the 24 hr. day sleeping, whereas on the study layovers they slept about 40% of the time. This suggests that they used the layover time for more sleep than they typically obtained at home, off duty. But when layover rest time (about 24 hr.) is added to subsequent duty work time (about 12 hr.), the result is a 36 hr. duty period. This represents roughly a 1:2 work:rest ratio (12 duty hr.:24 layover hr.). For crews in the current study the average duty period ratio ranged from 1:1.30 (SEL) to 1:2.79 (HNL2). Across 36 hr. duty periods, the average proportion of time crews spent asleep was 28%, which is 5% below what they typically obtained at home on a 24 hr. day. Consequently, when unencumbered by work during a 24 hr. layover period, crews slept proportionally more than when at home, but when the full 36 hr. work-rest cycle or duty period is considered, the proportion of sleep is significantly less than that obtained on a 24 hr. day at home. Hence, the increased amount of layover sleep obtained by crews is offset by their long duty period, resulting in a net loss of sleep for most crewmembers. It is unclear whether these results are unique to 24 hr. layovers, or whether cumulative sleep loss accrues for most crewmembers flying any long-haul trip schedule that involves layovers.

Finally, an analysis of the layover sleep episodes also revealed that approximately 40% of the sleep time was generally not obtained in one sleep period during the layover. Out of a total of 135 layovers, 77% involved two or more sleep episodes. Figure 27 displays the histogram of sleep episodes on layover. Most layovers involved two sleep episodes. There was a striking relationship between the duration of each sleep episode within a layover, as depicted in figure 28. Layover sleep durations were negatively correlated ($r = -.82$, $p < .0001$), such that when the first sleep episode in a layover was 6-11 hr. in duration, the second sleep episode either did not occur,

or if it did occur, it was under 4 hr. in duration. Conversely, when the first sleep episode was under 6 hr., a second sleep episode virtually always occurred and was between 4 and 11 hr. in duration. The fact that layovers tended to include two sleep episodes appeared to reflect a compromise between the influence of local layover time (e.g., food availability, quiet) and the influence of preferred circadian phases for sleep (ref. 3). A later report will review the timing of these layover sleeps and their relationship to crewmembers' home time.

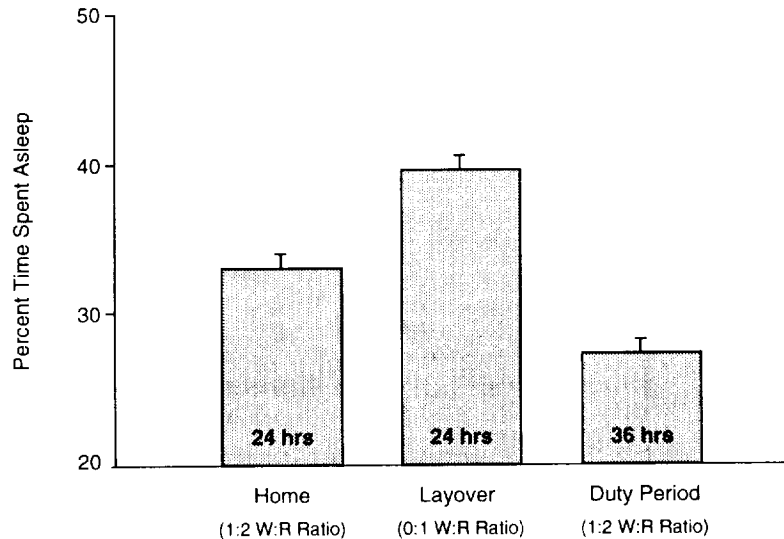


Figure 26. Mean (S.E.) proportion of time spent asleep when crews were off duty (home), when they were on layover (layover), and when layover was combined with duty time (duty period). W:R refers to ratio of time typically devoted to work (W) to that devoted to rest (R) within each time-frame. The duration of each time-frame is shown within the bottom of each histogram.

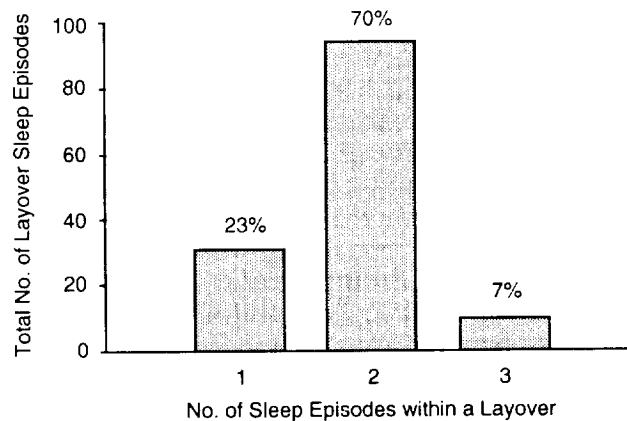


Figure 27. Total number of sleep episodes (by combined actigraph and sleep log) on layovers as a function of frequency of sleep episodes within each layover for all 21 study crewmembers (RG and NRG). Percentages reflect the proportion of each of the grand total of layover sleep episodes.

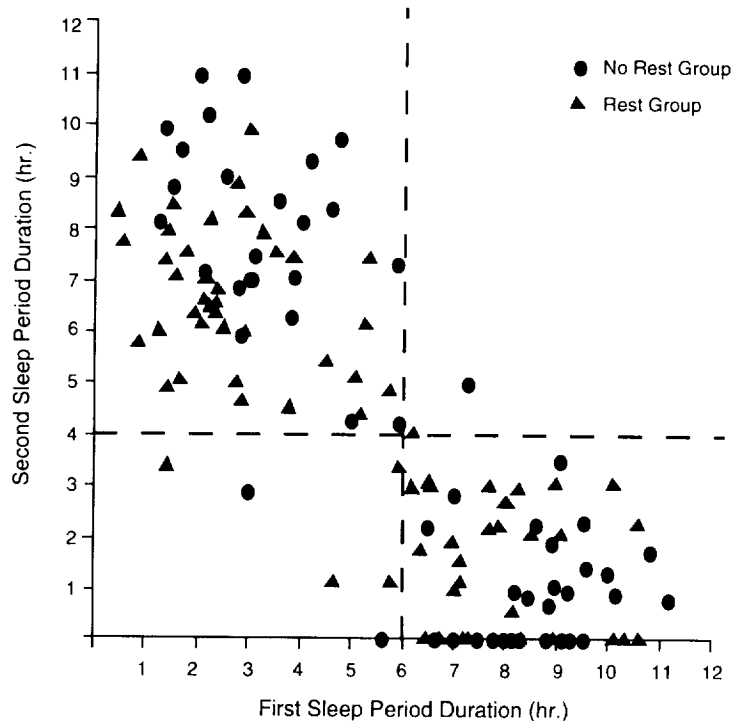


Figure 28. Duration of second sleep episodes on layover as a function of the duration of first sleep episodes for RG and NRG.

5.0 DISCUSSION

5.1 Study Limitations

This study involved only one trip pattern on a commercial airline. The study trip pattern was chosen according to predetermined criteria, but clearly the variety of trip schedules currently and potentially available is tremendous. Also, it is difficult to assess how the specific airline cultures may have affected the study outcomes. The study was conducted on transpacific flights to utilize the opportunity of scheduling the planned rest periods during cruise over water. Therefore, the low-workload portion of flight identified in this study occurred over water. The intense physiological and performance data collection occurred during a specific and restricted middle segment (four consecutive flight legs) of the trip schedule. Therefore, the initial home-to-flight-schedule transition is quantified only with logbook and actigraph data. Also, the final trip legs, which may represent the highest levels of accumulated fatigue, were not studied except for logbook and actigraph data. This study involved B-747 aircraft flown by three-person crews. Questions have already been raised regarding the applicability of this study to the two-person cockpit. There were two NASA researchers on the flight deck during the in-flight data collection periods. Although they were instructed to minimize their interactions with the crew and to make their presence on the flight deck as unobtrusive as possible, there is no question that having two extra persons in the cockpit may have potentially altered the regular flow of cockpit conversation and interaction. It is important to remain cognizant of these limitations when generalizing these results. As always, it is not appropriate to generalize the study results to scenarios that extend beyond the scope of the specific scientific issues addressed here.

5.2 Findings

5.2.1 EEG Sleep Results

On 93% of the rest period opportunities available for analysis, volunteer pilots were able to sleep in their cockpit seat. On average, they slept for 26 min., about 64% of the allotted rest opportunity. As a group, they took approximately 6 min. to fall asleep. The sleep was composed of 30% light sleep (NREM stage 1), 62% of slightly deeper sleep (NREM stage 2), and 8% deep sleep (NREM slow-wave sleep). There was no REM sleep (the sleep state associated with dreaming) observed in any of the naps. It generally can take 60-100 min. for the first occurrence of REM sleep during a regular nocturnal cycle of NREM and REM sleep states. Therefore, it was not expected that the 40 min. nap opportunity in this study would provide sufficient time for REM sleep to occur.

There were two significant findings that emerged from the analysis of the physiological sleep data obtained during the planned rest period. Both findings were related to the percentage of sleep stage that comprised the nap sleep in day versus night comparisons. A greater percentage of light sleep (NREM stage 1 sleep percent) occurred during day sleep than in night sleep, which was complemented by a greater percentage of deep sleep (NREM slow-wave sleep percent) during night sleep than in day sleep. Thus, sleep on day flights was lighter, and sleep obtained on night flights was deeper.

The physiological sleep data were also examined for evidence of sleepiness as indicated by the speed of falling asleep. One possible indication of cumulative sleep loss would have been a faster sleep latency across flight legs, demonstrating increased sleepiness as the trip schedule progressed. However, the results suggested that the RG pilots may have already been at a level of sleepiness that essentially did not allow room for further decreases.

An interesting finding emerged from analysis of the physiological data obtained during the NRG's control periods. Four of nine NRG subjects (44%) had at least one spontaneous episode of sleep during their 40-minute control period. The five sleep episodes lasted from a couple of minutes to over 12 min. To our knowledge, this is the first physiological documentation of an unplanned and involuntary sleep episode during long-haul flight operations. This study was the direct result of reports and anecdotal concerns regarding this kind of activity during long-haul flying. It should be noted that these episodes occurred in individuals aware that they were participating in a fatigue study, undergoing continuous physiological monitoring, and with two NASA researchers on the flight deck. For all of the "motivation" operating in this circumstance, it is clear that the physiological need for sleep was expressed. These findings clearly demonstrate the potential for fatigue and sleep loss to result in unplanned and involuntary occurrences of sleep in long-haul flight operations.

5.2.2 Vigilance/Sustained Attention: PVT Findings

The PVT data generally showed very consistent results across the analytical approaches. In response slowing (median RT), the NRG demonstrated a much greater range of average responses across flight legs and trials than the RG. The response slowing was most evident on the third in-flight trial on study flight legs 2, 3, and 4. On flight leg 1, the NRG and RG had comparable levels of performance. After leg 1, the NRG showed a steady increase in median RT across subsequent flight legs, with significant differences in the middle and at the end of flights. However, the RG did not show these significant changes in RT across flight legs and instead maintained a generally consistent level of performance. Overall, the NRG demonstrated median RTs 10%-16% slower than the RG during in-flight trials and the postflight trial.

There were a total of 283 lapses (i.e., response delay, block, or gap) for all 21 crewmembers, about 1% of all PVT responses. Lapses rarely occurred on early flight legs but increased in frequency as the trip schedule progressed. There were more lapses in the NRG (58% of all lapses) and on night flights for both groups (60% of all lapses). In-flight, the RG (with fewer subjects) had a total of 81 lapses, and the NRG had a total of 124. There was a prominent increase in the

NRG in-flight lapses during trials 2 and 3, though this did not occur in the RG. This suggests that the RG nap after in-flight trial 1 decreased the likelihood of increased lapsing later in the flight. However, there were also wide individual differences in lapse frequency, with five of nine NRG subjects with 10 or more in-flight lapses. Two of these subjects had relatively high numbers of lapses (i.e., 45 and 33). Only 3 of the 12 RG subjects had 10 or more in-flight lapses, with none higher than 14. At TOD on night-flight leg 4, both groups had more lapses than at TOD on night-flight leg 2. However, the NRG had an increase twice as large as that seen in the RG.

The time-on-task PVT performance metric was analyzed as an index of fatigueability (vigilance decrement function) and allowed the comparison of pilots' results with previous laboratory research (ref. 50). Regression lines were fitted to average response speed across the PVT for the RG and NRG on day-flight legs and night-flight legs. This allowed comparison of these two conditions with each other and with laboratory collected PVT data from college students after a normal night's sleep and after a night of sleep loss. Overall, the RG had a higher mean response speed than the NRG. The in-flight mean performance level (y-intercept of the vigilance decrement function) and fatigueability (slope) for the RG was close to that seen in nonsleep-deprived young college students. In contrast, during night flights, the NRG fatigueability function approached a level similar to that of healthy young adults deprived of one night's sleep. One important and significant outcome was that only the NRG subjects showed greater fatigueability (slope) on night flights than on day flights. On night flights, the NRG average response speed slowed twice as fast with time on task as that observed in the RG. Therefore, the RG nap was associated with significantly less fatigueability during night flights than the NRG.

5.2.3 Physiological Alertness/Sleepiness Findings

Overall, microevents indicating increased physiological sleepiness demonstrated a range of individual differences and variability in their occurrence. For the descriptive analysis of the raw data, the cumulative total number of events for the fewer subjects and fewer opportunities in the NRG was 120 whereas there were 34 events in the RG. For the NRG, 98 total microevents occurred before TOD with 22 events from TOD through descent and landing; while in the RG, all microevents occurred before TOD. The NRG crewmembers had microevents throughout the final 90 min. of each study flight leg. For both groups, study leg 4 (a night flight) had the most microevent occurrences. Although the RG had fewer occurrences earlier in the schedule (only one on study leg 1), 82% of the RG microevents occurred on study leg 4. This suggests that the effectiveness of the nap may have diminished as the trip legs progressed and on the last night flight, a finding also evident in the PVT lapse data. Overall, 69% of the microevents occurred on the night flights, 64% for the NRG and 85% for the RG.

The statistical analysis of the physiological microevents took into consideration, and demonstrated further, the variability of occurrences. Overall, for the transformed data, the average total cumulative physiological microevents for the NRG (6.37) was 2 times greater than the average cumulative total RG microevents (2.90) ($p = .02$). Also, the NRG averaged more SEM microevents (3.72) than the RG (1.95) ($p = .048$). Most of the total microevents occurred in the shortest duration time bin (5-10 sec.). As expected, significantly more microevents that occurred before TOD. There were significantly more SEM microevents on the last study leg and significantly more cumulative total microevents and SEM occurrences on the night flights. Generally, this supports the observation that physiological alertness decreased as the trip schedule progressed, especially on night flights (most likely the effect of cumulative sleep loss and circadian phase).

The physiological microevent results parallel the findings for the PVT lapse data. The nap was associated with maintaining a more consistent pattern of performance, whereas the increased performance (lapses) variability was observed in the control NRG. In a similar fashion, the nap was associated with a more consistent level of physiological alertness compared with the increased variability of microevent occurrences observed in the control NRG.

Another physiological alertness/sleepiness finding emerged from the sleep latency data. In this study, the RG averaged 5.6 min. to fall asleep. (For the RG (24) subjects this average was 4.1

min.) The laboratory standard for a level of excessive physiological sleepiness is a sleep latency of 5 min. or less, sometimes referred to as the twilight zone (refs. 21, 27). This suggests that overall, this group of volunteers fell asleep quickly and close to the laboratory-determined range that indicates excessive physiological sleepiness.

Overall, these findings demonstrate that the sleep obtained by the RG during the planned rest period was subsequently associated with greater physiological alertness—indicated by fewer occurrences of EEG and EOG microevents during the last 90 min. of flight—than was observed in the NRG. Generally, the microevents were brief (5-10 sec.) and represented the overall occurrence of total cumulative microevents and SEMs. SEMs are most often associated with the transition from quiet, relaxed wakefulness to sleep onset. These events have been associated with the perceptual disengagement characteristic of the transition from wakefulness to sleep (refs. 38, 71). This situation and the occurrence of EEG alpha (quiet, relaxed wakefulness with eyes closed) and theta activity (light NREM stage 1 sleep) represent a reduced level of physiological alertness.

The occurrence of these physiological microevents may represent a state of increased vulnerability to decrements in vigilance and performance that is associated with sleepiness, sleep onset, and sleep. When extremely sleepy, falling asleep, or asleep, an individual's capacity to behaviorally respond to his or her environment can be greatly reduced. It is under these circumstances that performance decrements can significantly reduce the safety margin.

5.2.4 Layover and Cumulative Sleep Loss WAM Findings

Eighteen of the 21 crewmembers (86%) developed a cumulative sleep debt of at least 4 hr. by the ninth day of the duty cycle. The worst accumulation represented 22 hr. of sleep loss by the ninth day. The overall average accumulated sleep loss was about 9 hr. One subject (5%) gained at least 4 hr. by the ninth day, whereas two others had neither a sleep debt nor gain. There were no significant differences between the RG and NRG in cumulative sleep loss. Further analysis did not demonstrate a significant effect of the cockpit naps on the cumulative sleep loss in the RG. This supports the notion that the beneficial effects of the cockpit nap were not created by a reduction of the cumulative sleep loss experienced by the RG. Rather, the cockpit nap provided acute relief for fatigue and, though briefly improving alertness, did not allow enough sleep to overcome the sleep loss accumulated over several days. By the ninth day of the duty cycle, crewmembers had averaged a loss of about one full night of sleep, whether they had a cockpit nap or not.

When the entire 36 hr. duty period is considered (12 hr. duty cycle followed by a 24 hr. layover), the percentage of layover sleep time is 28%. This is roughly 5% less sleep than typically obtained on off-duty home days and accounts for the net sleep loss for most crewmembers.

The analysis of layover sleep patterns also demonstrated that 77% of the 135 layovers involved two or more sleep episodes. Most layovers (70%) had two sleep episodes. There was a significant and striking difference between the duration of each sleep episode within a layover. If a first sleep episode was long, 6-11 hr. in duration, then the second sleep episode was either under 4 hr. in duration or did not occur. Conversely, if the first sleep episode was short, under 6 hr., then there was almost always a second sleep episode that lasted between 4 and 11 hr. in duration. Future analyses will focus on the pattern of layover sleep relative to flight legs.

5.2.5 Subjective Alertness Ratings

The analysis of the alertness ratings showed that subjective alertness was lower on night flights than on day flights and after the rest/control period than before the rest/control period. However, this last finding varied with flight leg, with significant decreases in subjective alertness ratings pre- to post-rest/control period only for flight legs 2,3, and 4 but not for leg 1. It appears this effect was simply a decrease in subjective alertness across flight time. Overall, the nap did not significantly affect the subjective ratings of alertness. There is, generally, a well-documented discrepancy between subjective reports and physiological and behavioral measures. The results of this study add to this scientific literature. Although the physiological alertness and behavioral performance

measures demonstrated a clear improvement related to the cockpit nap, this was not reflected in the subjective reports of alertness. This again highlights the concern that sleepy pilots may not provide reliable subjective estimates of their physiological and behavioral state; it appears that the tendency is to underestimate the level of physiological sleepiness. The current analyses of the subjective alertness data were based on averaging responses because of missing data. Future analyses will explore alternative approaches.

5.3 Scientific and Operational Issues

Several specific scientific and operational issues were raised in the introduction of this report. These will be addressed first, based on the results of the study. Next, other questions will be raised and addressed that are related to the study outcomes or to the operational implications of the results.

1. Given the opportunity, will pilots be able to sleep in their cockpit seats? What will be the quantity and quality of the sleep obtained in the cockpit environment?

On 93% of the rest period opportunities, the pilots were able to sleep in their cockpit seat. Generally, they fell asleep quickly (in about 6 min.) and slept for about 26 min. (64% of the 40 min. rest period). The physiological sleep data demonstrated that the pilots were able to sleep on both day and night flights, and there were no significant differences related to trip legs, halves of the trip, or flight deck position. The sleep obtained on day flights had a higher percentage of light sleep, whereas the sleep obtained during night flights had a higher percentage of deep sleep, although all naps contained proportionally more light (stage 1) than deep (slow-wave) sleep. Another interesting finding was that the average time to fall asleep (about 6 minutes) was close to the level of excessive physiological sleepiness found in sleep deprived laboratory subjects and in sleep disorders patients.

All pilots who were given the opportunity to nap in-flight were able to do so on at least three of the four flight legs.

2. Will a nap improve subsequent performance, such as sustained attention or vigilance, or prevent it from worsening? Will performance be maintained or improved during critical phases of operation, such as descent and landing?

All PVT performance parameters improved as a result of the nap. Generally, the reaction-time/performance data showed no differences between the RG and NRG before flight. However, on a variety of performance factors (e.g., response slowing, lapsing, optimal responding) the RG clearly demonstrated better performance than the NRG during flights, especially just before TOD on night flights. The NRG showed worse PVT performance across flight legs, and on night versus day flights, and the performance grew progressively worse within flight legs, with poorest performance near the end of the flights. However, the nap in the RG resulted in the maintenance of consistent performance across flight legs, on day versus night flights, and within flight legs, with no significant change in performance near the end of flights. Therefore, the RG nap appeared to mitigate the performance decrements that were observed in the NRG.

3. Will a nap improve subsequent alertness, as indicated by physiological measures of alertness/sleepiness, or prevent it from worsening? Will alertness be maintained or improved during critical phases of operation, such as descent and landing?

The EEG and EOG microevents indicating reduced physiological alertness clearly differentiated the NRG from the RG. The sleep obtained during the planned rest period in the RG was followed by fewer microevents (i.e., indicated a higher level of physiological

alertness) in the last 90 min. of flight than in the NRG. The overall rate of microevent occurrence was 2 times greater in the NRG. There were no occurrences of microevents during the last 30 min. of flight in the RG, whereas there were 22 microevents during descent and approach in the NRG. Overall, the RG nap was followed by a higher level of physiological alertness than was measured in the NRG, including during the critical phases of operation during descent and landing.

4. If a planned nap improves alertness and performance, how long do the positive effects last?

There were significant positive effects on both performance and alertness as a result of the cockpit nap. This study does not provide an answer as to the duration of the positive effects beyond the several hours post-rest period in this study. It is not possible to determine whether the effects would have been maintained another 30 min., 1 hr., 2 hr., etc.

Conceptually and operationally, methods to minimize or mitigate the effects of sleep loss, circadian disruption, and fatigue in flight operations, can be divided into two main approaches: preventive strategies and operational countermeasures. Preventive strategies involve those approaches that result in more long-term adjustments and effects on underlying physiological sleep and circadian processes. Examples of potential preventive strategies that require future research are pre-shifting of the circadian phase before multiple time-zone changes, the use of bright light or exercise or both to rapidly readjust the circadian clock to a new time zone, and maximizing the quantity and quality of sleep before, during, and after trips. These preventive strategies affect underlying physiological sleep need, sleepiness, and circadian phase in a more long-term or chronic manner. Operational countermeasures are focused, acute strategies to reduce sleepiness and improve alertness and performance during actual operations. These short-acting countermeasures are not intended to relieve underlying physiological sleepiness but rather to increase alertness and performance during operational tasks. Examples of proved operational countermeasures are the judicious use of caffeine, increased physical activity, and increased interaction. One acute, short-acting operational countermeasure that can temporarily reduce physiological sleepiness is prophylactic napping (ref. 13). A short nap will not reverse a severe, accumulated sleep debt, but it can reduce sleepiness and improve performance for some finite period after it. The planned cockpit nap in this study would be considered an operational countermeasure that provided an acute, short-acting improvement in alertness and performance. Therefore, the cockpit nap would not be expected to provide long-term relief or to alter the underlying circadian and physiological processes to any great extent. This is substantiated by the study results that indicated that the cockpit nap had no effect on layover sleep.

It has been noted that differentiating countermeasure approaches in this manner is analogous to the concepts of error resistance and error tolerance (ref 72). Error resistance is designed and built into a system to reduce the initial occurrence of errors. However, acknowledging that this error resistance may not be absolute, error-tolerant designs provide another level of error protection. Similarly, preventive strategies may minimize some or many of the effects that might result from the sleep loss, circadian disruption, and fatigue in long-haul flight operations. Operational countermeasures provide the next level of acute intervention (i.e., like error tolerance), acknowledging that the preventive strategies may not be absolute.

5. Could planned rest opportunities, and sleep, compromise flight safety? Will sleep inertia (i.e., the grogginess and disorientation sometimes experienced when awakened from deep sleep) be a safety concern?

Data on sleep inertia were not available in this project, a result of a measurement limitation. The specific procedural and safety guidelines were followed with no significant deviations, however. There were no reported or observed events that suggested the cockpit naps adversely affected any operational parameters. There are currently no data, anecdotal or in

the PVT results, to suggest that sleep inertia was an issue. The 20 min. period following the nap appeared to provide enough time to allow a return to full recovery from any sleep inertia and to prepare pilots to reenter the operational loop. The short duration of the nap may have been an important factor, since deep sleep, which is associated with sleep inertia, was minimal (8%).

6. What operational and safety guidelines should be considered for implementation of planned cockpit rest in long-haul operations?

There were eight specific procedural and seven safety guidelines that were successfully implemented in this initial study. However, not all of these would be necessary for a general implementation of planned cockpit rest periods in long-haul flight operations (e.g., two NASA researchers on the flight deck). The following operational and safety guidelines would be the priority considerations for implementation: (1) It was crucial that the rest period was planned with first choice for timing of the nap going to the landing pilot; (2) The rest periods were scheduled during a low workload phase of flight and ended 1 hr. before descent; (3) Only one crewmember was scheduled to rest at a time with a clear rotation plan established before takeoff; (4) The rest opportunity was divided into an initial preparation period, followed by the 40 min. rest period, followed by a recovery period; (5) The rest was terminated at a preset time by a researcher (i.e., an external source) and the resting pilot was fully briefed before reentering the operational loop; (6) It was established that the captain would be notified immediately of the first indication of any potential anomaly; and (7) The safe and normal operation of the aircraft was given the highest priority and, therefore, no cockpit rest procedure or activity was allowed to interfere with this.

7. Would sanctioned planned cockpit rest periods be an improvement over the current situation of uncontrolled spontaneous napping and nonsanctioned naps in nonaugmented long-haul flying?

Evidence has been cited that both uncontrolled spontaneous napping and nonsanctioned naps occur in long-haul flight operations. Cockpit observers have noted the occurrence of naps in long-haul commercial operations (ref. 12). Gander et al. reported logbook data that provided subjective reports of in-flight naps in long-haul flying (ref. 3). This study provided physiological documentation of spontaneous sleep episodes that occurred during the NRG control period.

In this study, the RG was able to obtain sleep on 93% of the planned opportunities. This planned nap was associated with better subsequent physiological alertness and psychomotor vigilance performance in comparison with the NRG. The nap resulted in the maintenance of consistent behavioral performance and vigilance. The measures of physiological alertness also indicated that the RG nap was followed by a higher level of alertness during the last 90 min. of flight than for the NRG. Therefore, the sleep obtained during the planned cockpit rest period resulted in levels of performance and alertness that raised the safety margin when compared with the decreased performance, reduced physiological alertness, and unplanned napping that occurred in the NRG.

In contrast to the current operational situation, this study provided a planned opportunity to sleep, a controlled nap length, and a specified rotation during a low-workload phase of flight. Also, this study demonstrated that planned cockpit rest periods could be implemented according to procedural and safety guidelines that had minimal effect on normal flight operations and, in this study, were associated with no adverse operational effects. These considerations suggest that a planned cockpit rest period would be an improvement over the current situation in nonaugmented long-haul operations.

8. Could the positive effects of the rest periods on PVT performance be explained by motivational factors? That is, did the RG simply try harder, or the NRG try less hard?

Certainly motivation is essential for any kind of performance assessment, and every effort was made in the current study to ensure that crewmembers in both groups performed the PVT task with the highest motivation, always trying to better their performance on it. There are two reasons that suggest that the current results are not attributable to differential motivation on the part of the two groups. First, if the NRG was not as motivated to perform as the RG, there should have been performance differences evident between groups on flight leg 1 and at preflight PVT trials for all four flight legs. This clearly was not the case; rather, performance differences emerged during in-flight trials, especially following rest trials on night-flight legs, precisely the time when fatigue should have resulted in the most adverse effects on PVT performance. Second, the analysis of EEG microevents following rest substantiates the PVT findings. If the performance results were due primarily to differential motivation, there is no reason why the NRG should have had more EEG microevents indicative of increased physiological sleepiness. This fact, and the lack of other evidence that motivation was different between groups, suggests that the PVT performance results genuinely reflected differences in attentional capacity and response speed between groups.

9. Do the performance differences between groups have any relevance to aircraft operation? In other words, what is the operational significance of the PVT differences between groups?

As indicated in the methods section, the PVT probed one aspect of the behavioral capability of the aircrews, and is *not* specifically a measure of operational performance. However, high levels of performance on the PVT require sustained attention for 10 min. and the fastest response times a person can produce. To the extent that attention and rapid responses are critical features of many tasks involved in the safe operation of an aircraft, the PVT results can inform us about operational readiness. Indeed, it is not unreasonable to assert that during flights, crews should avoid missing signals (i.e., lapses), avoid false responding, and avoid slowed responding, and that if they are having difficulty doing so on the PVT, then there may be some increased likelihood that they will have difficulty doing so on operationally relevant tasks. Finally, in order to understand the relevance of the PVT results in flight crews, comparisons of these study results with data from sleep-deprived young adults and other relevant groups who have been studied are currently in progress. There is some evidence (see fig. 21) that during night flights, no-rest crews were performing on the PVT at a level approaching that of young adults deprived of a full night of sleep. It is reasonable to consider this level of fatigue as operationally undesirable.

10. How robust and solid are the study results?

The findings for the PVT are enhanced by the consistency of the data across the different analytical approaches. Whether examining lapses, optimal responding, etc., the direction of the results demonstrated the effectiveness of the cockpit nap in maintaining consistent behavioral performance across these dimensions. The physiological microevent data converge with the performance data to provide even stronger evidence for the benefits of the planned cockpit nap. Therefore, it is the combination of the performance and physiological data that provides the greatest confidence in the study results, with both clearly demonstrating the benefits associated with the cockpit nap.

11. What is the significance of the discrepancy between subjective reports and the other performance and physiological measures?

The scientific literature generally demonstrates a discrepancy between subjective reports and psychophysiological measures, especially regarding sleep and sleepiness (e.g., ref. 23). Therefore, it is not surprising to find that the RG pilots were not able to discriminate

subjectively the improvements associated with the nap that were demonstrated in the performance and physiological data. This raises an extremely important point supported by previous research (refs. 39, 40). Generally, when sleepy, pilots will provide subjective reports that do not correspond to their behavioral or physiological state. That is, asking pilots to rate their alertness/sleepiness will not ensure an accurate assessment of their status. This is especially important for flight safety since the tendency is to *underestimate* physiological sleepiness.

12. How much will cockpit naps affect layover sleep?

Analysis of the actigraphic data demonstrated that the amount of sleep obtained during the cockpit nap did not affect subsequent layover sleep. In fact, overall, about 85% of the study sample accumulated a sleep debt over the course of the flight schedule. This supports the notion that the short-acting nature of this brief nap did not affect subsequent layover sleep or circadian rest/activity patterns, as determined by actigraphic data. On the other hand, knowing that one is going to have a nap opportunity in-flight may prompt some crewmembers to avoid napping on layover in the hours immediately before coming on duty.

(There are several other scientific and operational questions that emerge from the study results or are suggested by the potential use of planned cockpit rest periods. Some of these questions follow.)

13. Should the length of the cockpit rest period be longer or shorter?

This study did not specifically address the effects of nap duration on alertness. Current laboratory data, however, suggest that the cockpit rest period should not be longer than an hour in order to avoid major sleep inertia and effects on layover sleep (see ref. 19, for a review). It is unclear how much less than an hour might be an effective rest period. The 40 min. planned rest period in this study improved subsequent performance and alertness and provided a sufficient length of time for the 26 min. nap that occurred. Each rest period was divided into three phases that totaled about 60 min. The first phase required 3-5 min. for preparation before the rest period, the rest period itself was 40 min. long, and the recovery phase was 20 min. It may be possible to shorten the recovery time to a 10-15 min. period allowing time for sleep inertia to dissipate if present and to brief the rested pilot before reentering the operational loop. This could reduce slightly the overall amount of time required for the entire rest period procedure.

14. What should be considered in determining where within the flight leg cockpit rest period should be scheduled?

The primary concern in this study was to utilize a low-workload phase of flight. During the transpacific schedules studied, this involved cruise over water. The low-workload, cruise portion of flight seems to be the crucial factor in scheduling the rest period; whether it takes place overwater may be less crucial. However, procedural and safety guidelines for flights over congested land areas were not addressed in this study.

15. Should planned cockpit rest periods be considered for implementation in two-person crews?

As indicated in several previous areas of this report, this study does not provide data on the use of planned cockpit rest periods in two-person flight operations. In consideration of the potentially long flight lengths of two-person automated aircraft, the future increased use of two-person crews, and the fact that these two-person crews will face similar sleep loss, circadian disruptions, fatigue, and sleepiness when flying long-haul operations, the potential use of planned cockpit rest should be studied in that environment. A primary concern, as generally raised with two-person operations, is that the redundancy in the system is reduced by

one human. In the current study, there were two pilots maintaining the flight while one rotated through the planned rest period. In a two-person crew, the pilot remaining awake has added responsibility to maintain wakefulness, vigilance, and level of performance. One possible approach is the development of operational countermeasures that utilize the automation available in the cockpit to maintain alertness in the awake crewmember (refs. 2,10). Another possibility is to consider whether other personnel may be made available to assist the awake crewmember in maintaining alertness while the other pilot naps.

16. Is a rest period the same as a sleep period?

NO. It has been shown clearly that rest is not the same as sleep (ref. 73). A rest period with reduced physical or mental activity does *not* produce the same effects as sleep. Sleeping is a vital biological function like eating and drinking (ref. 74). One result of an individual's inability to obtain the usual and required amount of sleep, whether related to multiple time-zone changes, a sleep disorder, or whatever, is physiological sleepiness (ref. 75). Only sleep can reverse this physiological sleepiness, a rest period can not. Some activities can mask the level of underlying physiological sleepiness and acutely increase the level of subjective alertness.

This point is raised to address the purpose of the planned cockpit rest period. Although evidence suggested that pilots would be able to nap if given the opportunity, one purpose of this study was to determine how often sleep would occur within the rest period. That is, a rest opportunity period could be provided, but would pilots be able to nap during this period in their cockpit seats? Obviously, yes they can, and did so on 93% of the rest opportunities. Therefore, in light of the study results and the previous point that rest is not sleep, the planned cockpit rest periods are more accurately identified as *planned sleep opportunities*. It is the planned opportunity for sleep that will provide the acute countermeasure and safety valve for the physiological sleepiness and fatigue experienced in long-haul flight operations.

5.4 Future Considerations

It is clear from the results of this study that planned sleep opportunities can significantly improve performance and physiological alertness in nonaugmented long-haul flight operations. The convergence of the behavioral performance data and the physiological data to demonstrate the effectiveness of the cockpit nap lend support to the robustness of the findings. However, the limitations of the study also must be acknowledged and the generalizability of the results should not be considered beyond the scope of the scientific and operational issues addressed.

The current results support the implementation of planned cockpit sleep opportunities in nonaugmented long-haul flight operations involving three-person crews. If planned cockpit sleep opportunities were sanctioned, each airline could determine the appropriate incorporation of procedures into its specific mode of operation following the guidelines established by the FAA. If implemented, a joint NASA/FAA follow-up study should be conducted within 6-12 months to examine how planned cockpit sleep opportunities have been incorporated into airline procedures. The study could examine how the procedures were implemented and their effectiveness. This might take the form of a survey or include some field data collection. The results of this follow-up study may lend support for further refinement of procedures and other future implementation.

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APPENDIX

PVT RESULTS

PVT Lapse Duration

The analysis discussed in the main body of this report focused on the frequency of performance lapses in crewmembers, whereas this analysis concerns the length or duration of lapses. In fact, the focus in this appendix concerns not only lapse duration, but also the speed of responses that comprise the poorest performance in a PVT trial. There is laboratory evidence that the speed of the slowest 10% of RTs in a trial decreases as sleep-based fatigue increases. The issue cannot be assessed statistically, however, without considering the proportionality between the mean of raw RT scores and the standard deviation (see ref. 6, especially fig. 2 therein). To correct for this proportionality and the overall distortion introduced by very long RTs, we performed a reciprocal transformation on the 10% of RTs that were of the longest duration in each trial, yielding response speeds for the lapse domain, and then analyzed the results using ANOVAs.

Figure 29 shows the average speed of the slowest 10% of PVT responses for NRG and RG for each trial of each study flight leg. (*Note: Because of the reciprocal transformation, poorer performance is reflected in a downward direction in figs. 28-30.*) As with previous performance parameters in this report, the NRG displays far greater range of average speeds across flight legs and trials than the RG, with drops in mean speed especially evident on the third in-flight performance trial on study flight legs 2, 3, and 4. The three-way ANOVA confirmed this picture. The main effect for condition was marginal ($F_{1,19} = 3.54$, $p < .075$), whereas the main effects for flight leg ($F_{3,57} = 6.44$, $p < .001$) and trial ($F_{3,57} = 8.44$, $p < .0005$) were significant. The condition by flight-leg interaction was significant ($F_{3,57} = 3.11$, $p < .033$), as was the flight leg by trial interaction ($F_{9,171} = 4.07$, $p < .0005$). The condition by trial interaction was marginal ($F_{3,57} = 2.56$, $p < .064$). The F-ratio for the three-way interaction was not significant ($F_{9,171} = 0.51$).

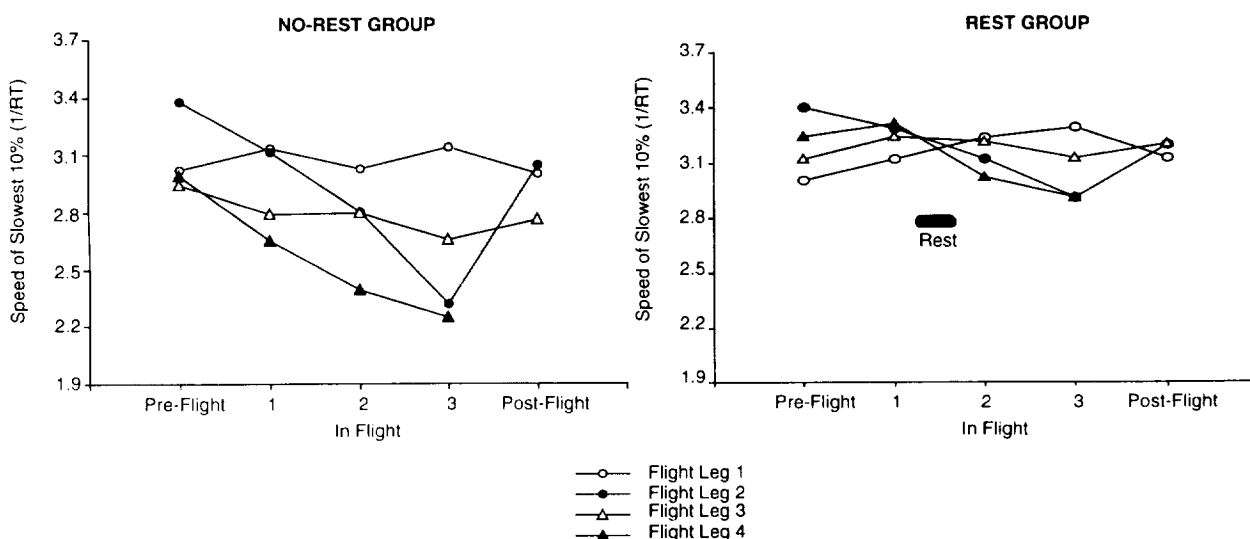


Figure 29. Mean response speed of lapses (the slowest 10% of PVT responses within each trial) for RG and NRG across each flight leg. The reciprocal transformation results in decreases indicating poorer performance (slower speed).

Two-way ANOVA revealed that there were no significant main effects or interactions on day-flight leg 1. On night-flight legs 2 and 4 there were significant main effects for trials (leg 2 $F_{4,76} = 9.99$, $p < .0005$; leg 4 $F_{3,57} = 5.48$, $p < .002$), indicating that response speed was slowing as flights progressed. Most important, there were significant main effects for condition on flight leg 3 ($F_{1,19} = 4.44$, $p < .05$) and flight leg 4 ($F_{1,19} = 5.40$, $p < .031$). Overall, the RG averaged less slowing of responses in the lapse domain than did the NRG, especially during these later flight legs. Figure 30 illustrates this effect using data from study flight legs 1 and 4. By flight leg 4 the speed of responses in the lapse domain for the NRG had decreased 21%-28% midway and late in the flight, compared to flight leg 1. No such decline in the speed of the slowest 10% is evident in the RG, suggesting that the nap prevented it.

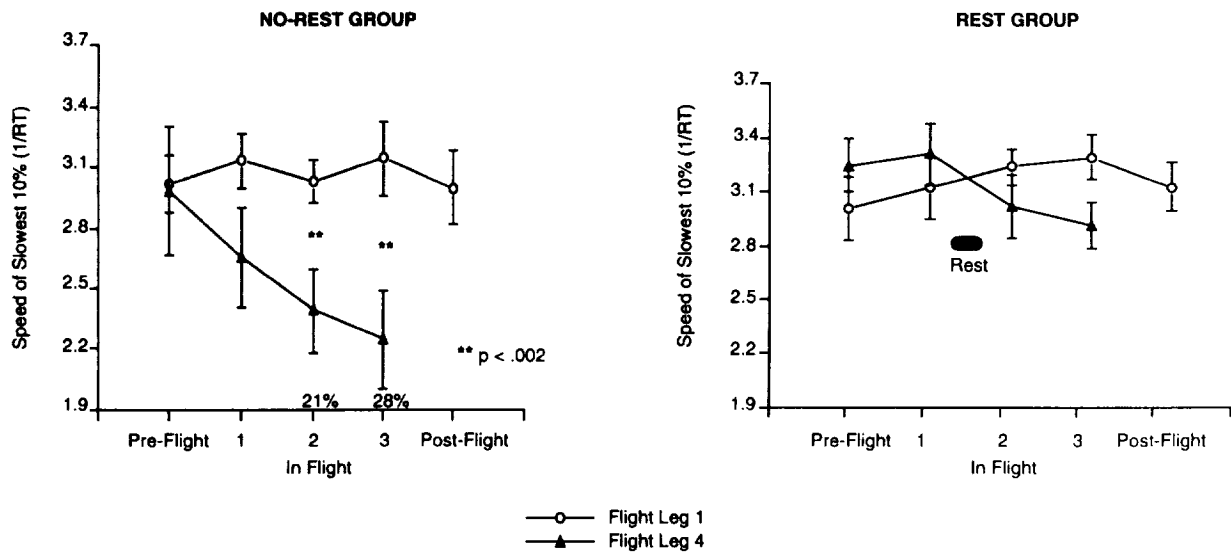


Figure 30. Mean response speed (S.E.) of lapses (slowest 10%) for RG and NRG for day-flight leg 1 and night-flight leg 4. Decreases indicate poorer performance (slower speed). Asterisks indicate significant differences with group by paired t-tests at specific time points.

Figure 31 shows the difference in lapse domain response speed between the two groups for data averaged across the four study flight legs. The NRG response averaged 12%-15% slower than those of the RG during in-flight trials 2 and 3.

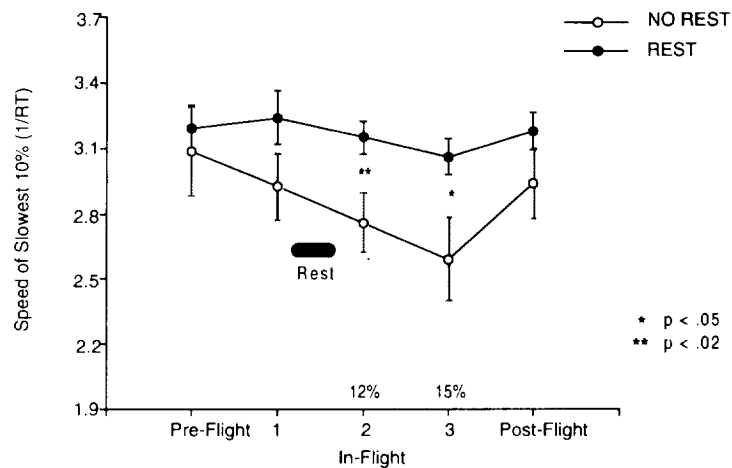


Figure 31. Mean response speed (S.E.) of lapses (slowest 10%) for RG and NRG collapsed across all four flight legs. Decreases indicate poorer performance (slower speed). Percentages indicate differences between groups' means at PVT trial times. Asterisks indicate significant differences between groups by independent t-tests at specific time points.

PVT Optimum Response Time

Optimum response times are the opposite of the lapse domain. They refer to the 10% of RTs in a PVT trial that have the shortest durations, and therefore reflect the best performance on a given trial. Although it has often been assumed that sleep loss and fatigue should not affect the very fastest reaction times, there is now ample evidence that this assumption is incorrect (ref. 6). Diminution of "best effort" as reflected in small but statistically significant shifts in the upper 10% of responses has been found in both the classic research on the effects of sleep loss on performance (ref. 67), and in recent studies (ref. 60).

Performance from the present study was analyzed to determine whether the Rest condition had any effect on optimum responses, as well as to ascertain what, if any, effects night flights had on RTs in the domain of "best effort." In conducting these comparisons, the same basic analytic strategy used with other performance parameters was followed, except that no distribution-free metric or transformation was necessary because optimum responses have exceedingly low variability (by definition they are uninfluenced by lapses).

Figure 32 displays the average optimum RTs for no-rest and rest groups for each trial of each study flight leg. (Note that because these analyses use raw RT scores, poorer performance is reflected in an upward direction in figs. 32-34.) It is clear upon examining the figure that, as expected, there is little variability across trials and flight legs for either group, although there appears to be some change evident in the NRG that is absent in the RG. The three-way ANOVA yielded a main effect for condition ($F_{1,19} = 7.79, p < .012$), flight leg ($F_{3,57} = 2.90, p < .042$), and trial ($F_{3,57} = 12.70, p < .0005$). There were significant interactions for condition by trial ($F_{3,57} = 3.55, p < .02$), and for flight leg by trial ($F_{9,171} = 2.29, p < .022$). The overall interaction was not significant.

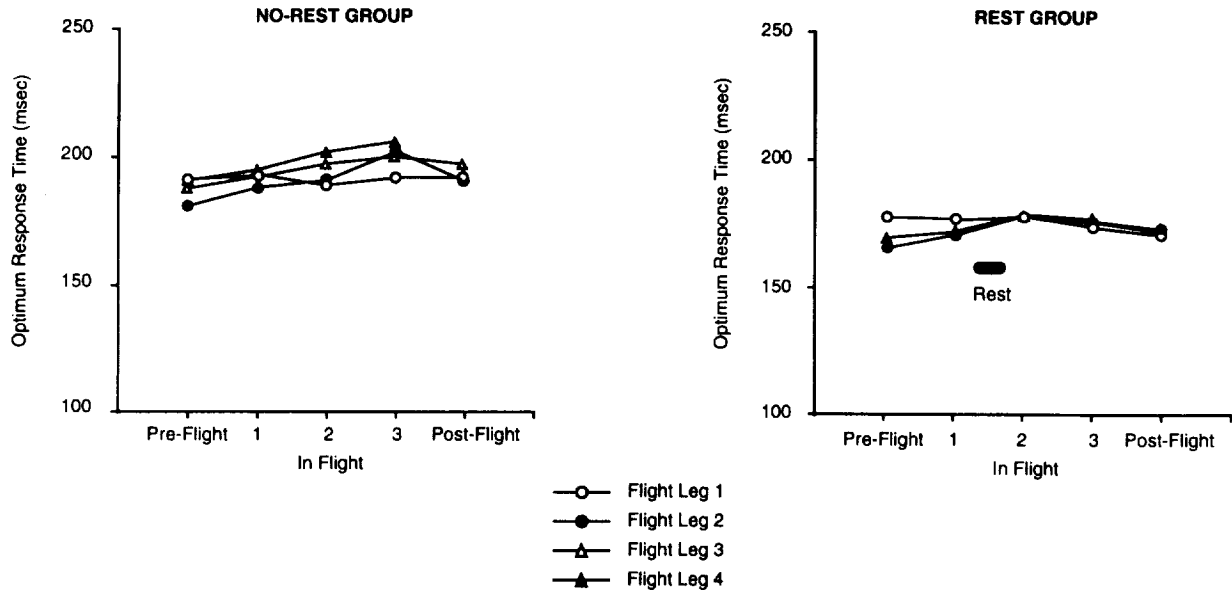


Figure 32. Mean optimum response times (the fastest 10% of RTs within each PVT trial) for RG and NRG across each flight leg. Increases indicate poorer performance.

Figure 33 compares the means for flight legs 1 and 4 within each group. There is a nonsignificant trend for optimum performance to be slightly slower at TOD during leg 4 in the NRG. ANOVA within each flight leg yielded no significant main effects or interactions on flight leg 1—the two groups were performing comparably at this time, although there was a trend for the RG to average slightly faster optimum RTs ($F_{1,19} = 4.05$, $p < .058$). On study flight legs, 2, 3, and 4, the NRG was significantly slower in optimum responses than the RG (main effect for condition: leg 2 $F_{1,19} = 7.93$, $p < .014$; leg 3 $F_{1,19} = 8.16$, $p < .01$; leg 4 $F_{1,19} = 10.01$, $p < .005$). An analysis of covariance, with the first trial on leg 1 as the covariate, reduced these main effects due to condition, but did not eliminate them (leg 2 $F_{1,18} = 3.71$, $p < .07$; leg 3 $F_{1,18} = 4.50$, $p < .048$; leg 4 $F_{1,18} = 5.92$, $p < .026$).

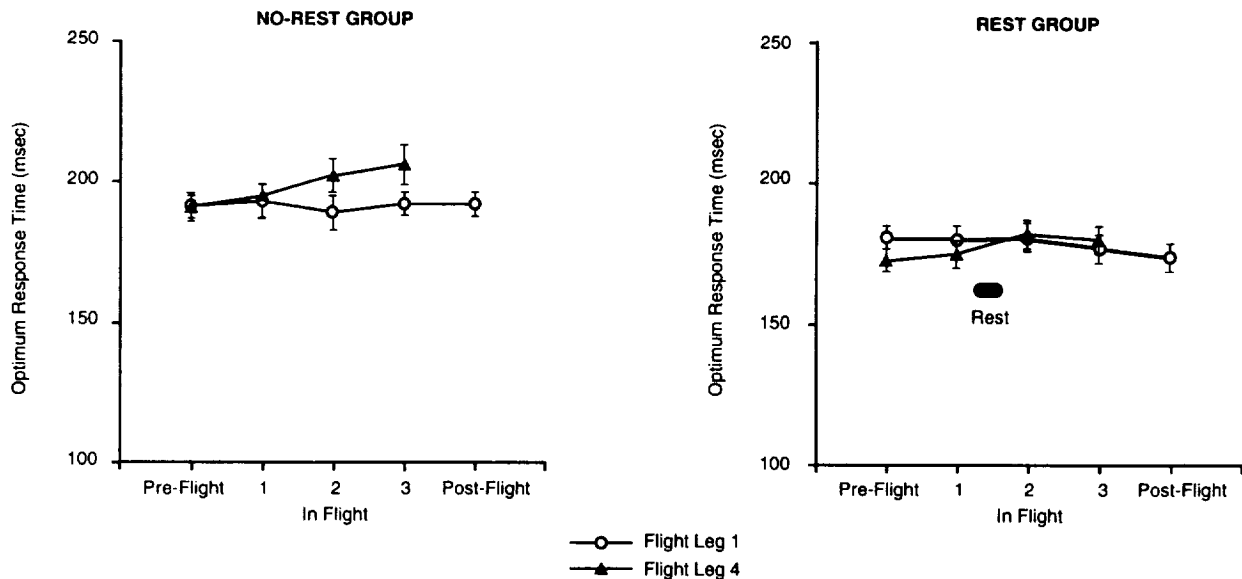


Figure 33. Mean (S.E.) optimum response times (the fastest 10% of RTs within each PVT trial) for RG and NRG for day-flight leg 1 and night-flight leg 4. Increases indicate poorer performance.

Figure 34 shows the difference in optimum responses at each trial time-point between the two groups for data averaged across the four study flight legs. Although very modest (8%), the average difference between the RG and NRG near TOD was statistically significant (the postflight difference is less meaningful owing to the absence of a postflight trial on leg 4).

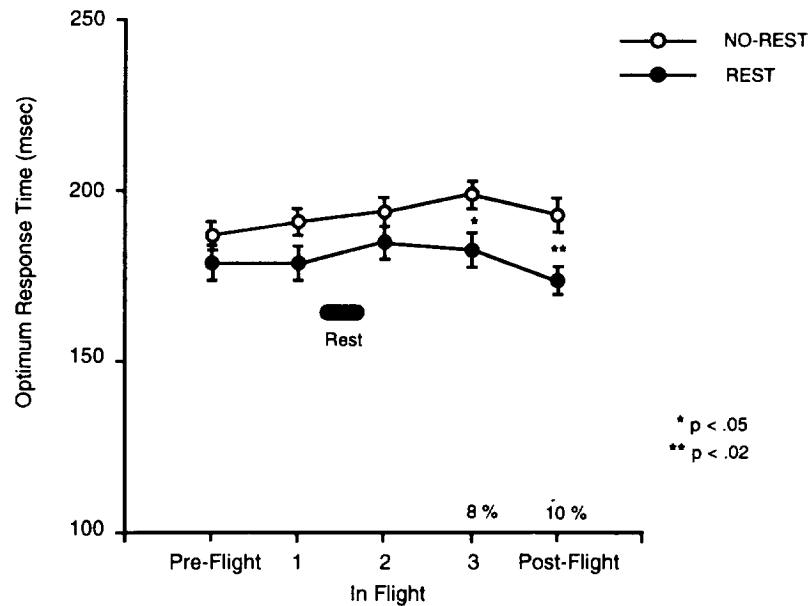


Figure 34. Mean (S.E.) optimum response times (the fastest 10% of RTs within each PVT trial) for RG and NRG collapsed across all four flight legs. Increases indicate poorer performance. Percentages indicate differences between groups' means at PVT trial times. Asterisks indicate significant differences between groups by independent t-tests at specific time points.

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